Surface-Energy Balance Methods for Estimating ET: Current State-of-the-Art and Recent Developments

Landsat "8" – launched Feb. 2013

Rick Allen -- University of Idaho, Kimberly, Idaho

Professor of Water Resources Engineering
Member, USGS/NASA Landsat Science Team

Ayse Kilic – University of Nebraska, Lincoln

Assoc. Professor of Civil Engineering / School of Natural Resources
Member, USGS/NASA Landsat Science Team

Justin Huntington, Desert Research Institute, Reno, NV

Other Partners: Ricardo Trezza, UI; Jan Hendrickx, NMT; Babu Kamble, UNL; Jeppe Kjaersgaard, UMn

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A LEGACY OF LEADING

Who Cares about ET?

- Departments of Water Resources
- US Bureau of Reclamation
- US Geological Survey
- Environment
- Irrigators
- Courts

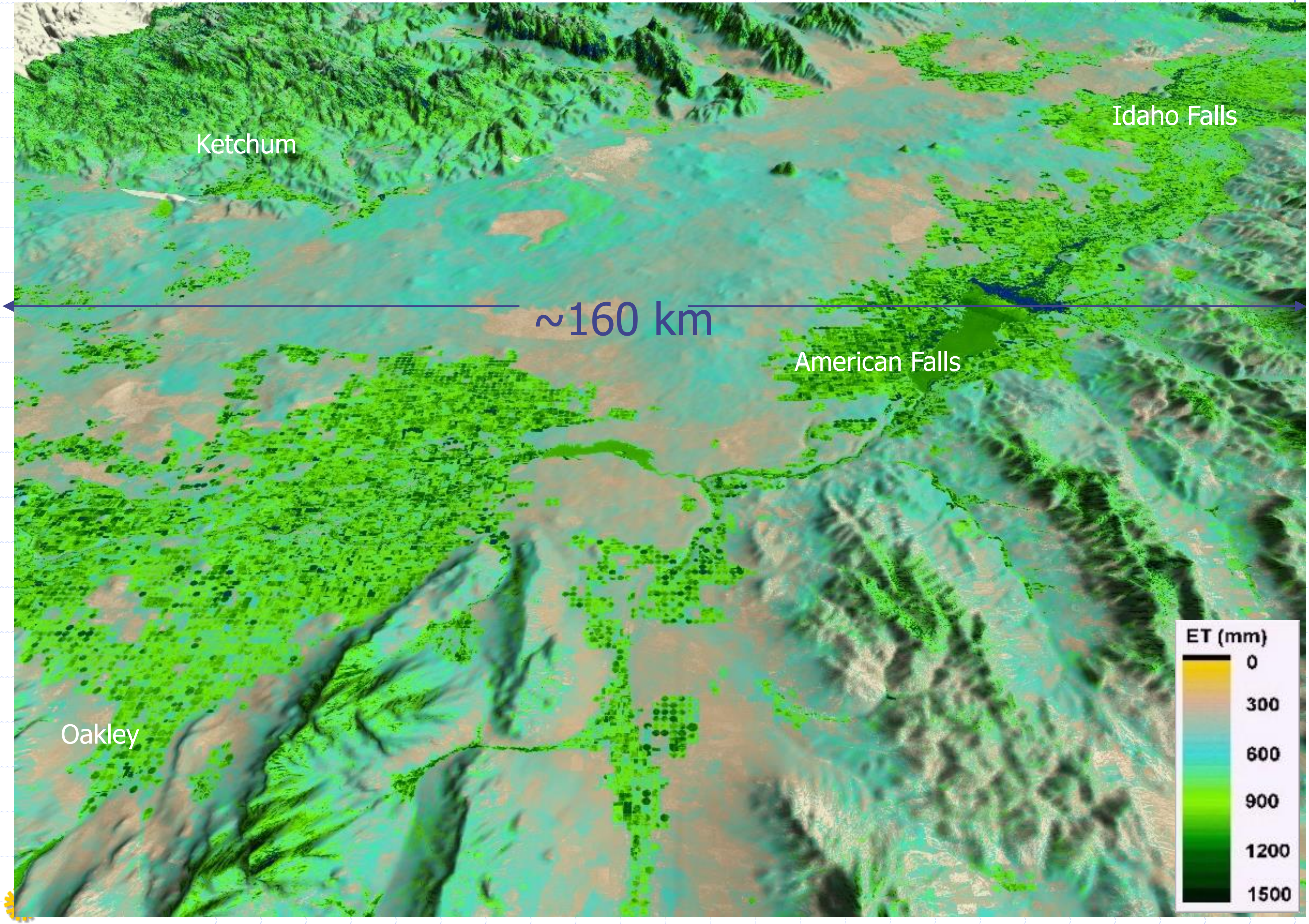


Applications in the West

- **Water Planning**
- **Aquifer Depletions**
- Hydrologic Modeling
- Endangered Species
- Agricultural Water Use
- **Legal Finding-of-Fact**
- **Water Rights Buy-Back**
- Water Rights Compliance
- **In-Season Water Demand**
- Tribal Water Rights Negotiations

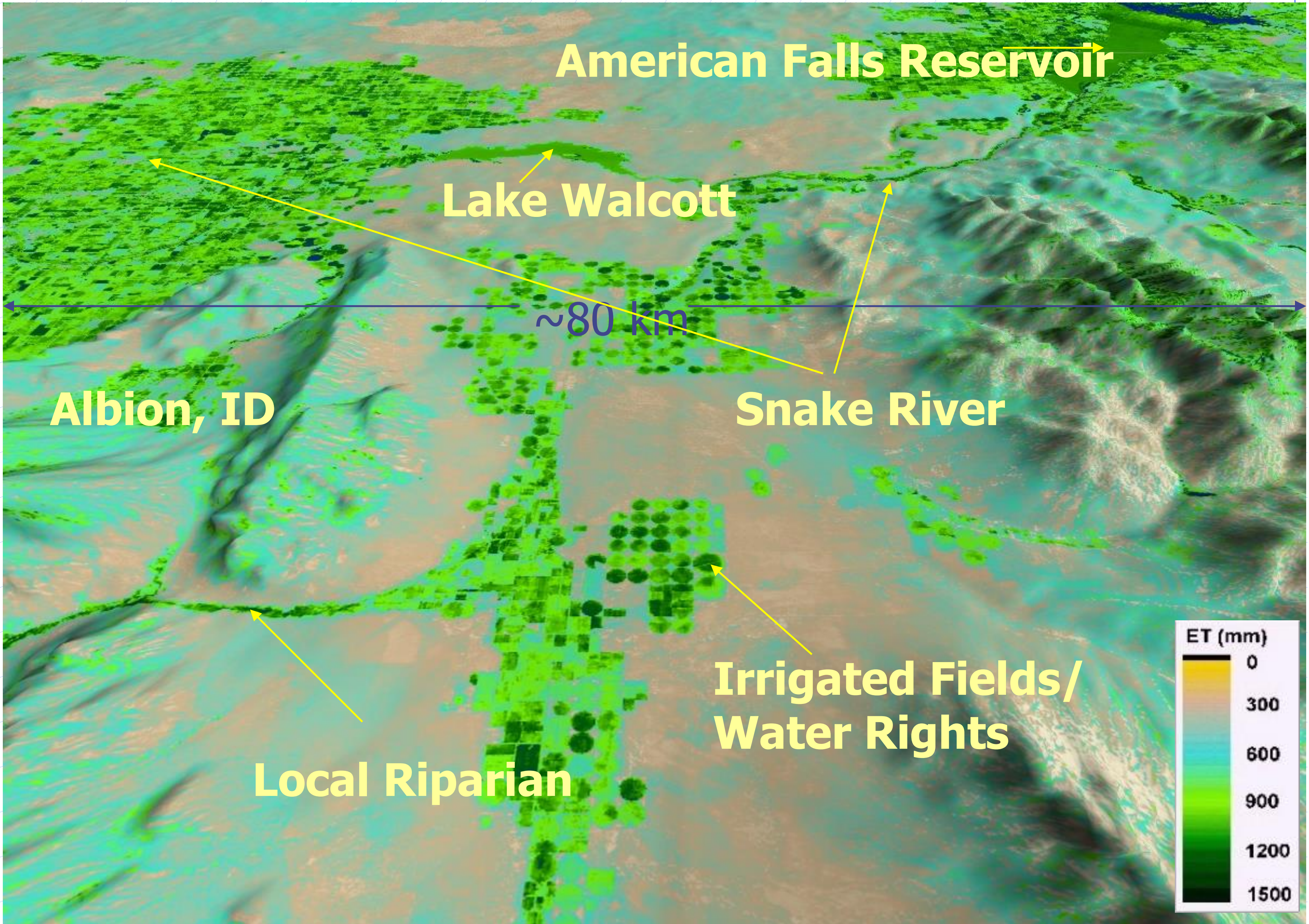
Does ET vary in Space? (Yes!) -- Monthly and Seasonal ET at 30 m resolution for the Eastern Snake Plain of Idaho

April – October, 2006 ET



ET features at 30 m resolution

April – October, 2006 ET from METRIC-Landsat



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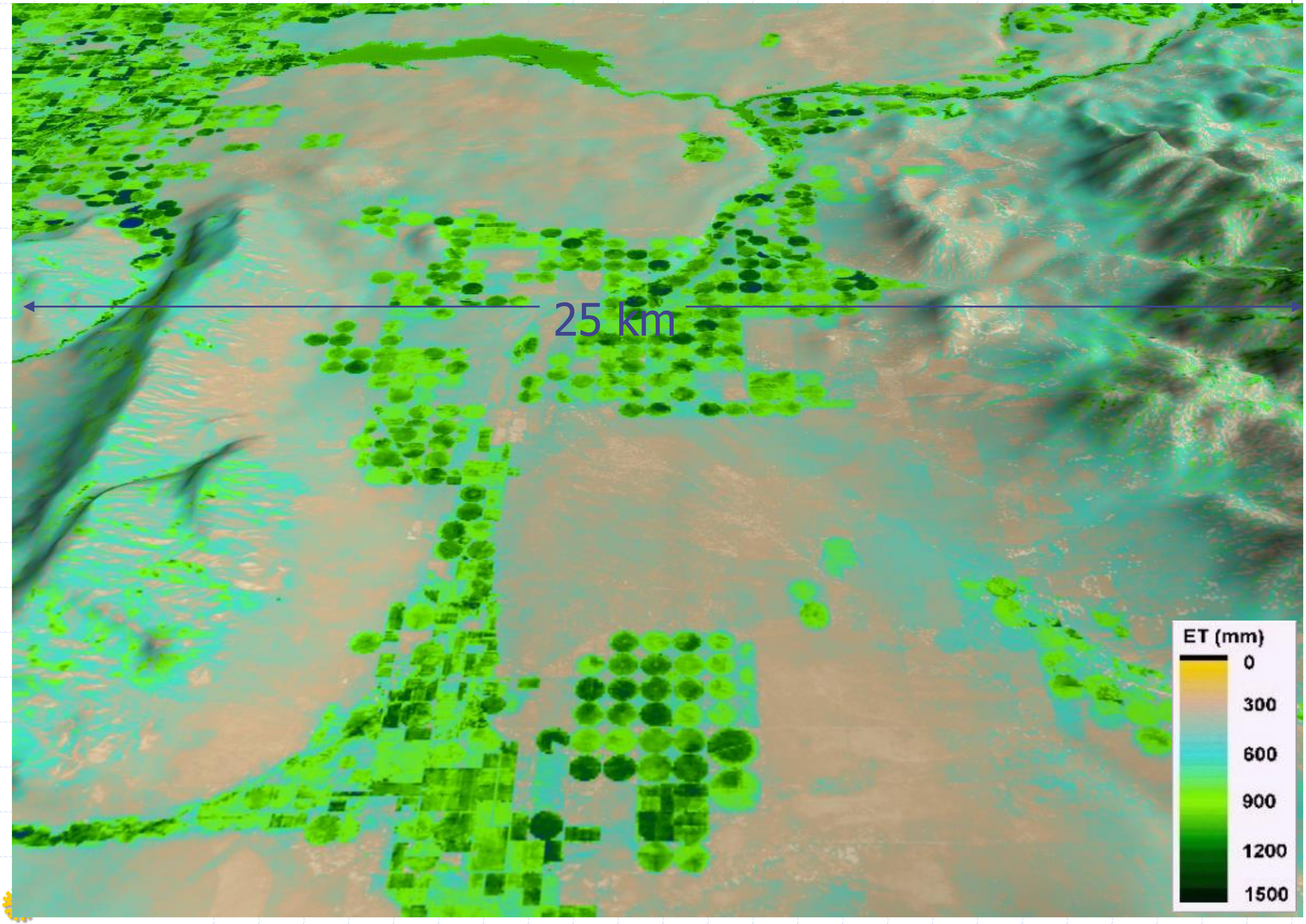
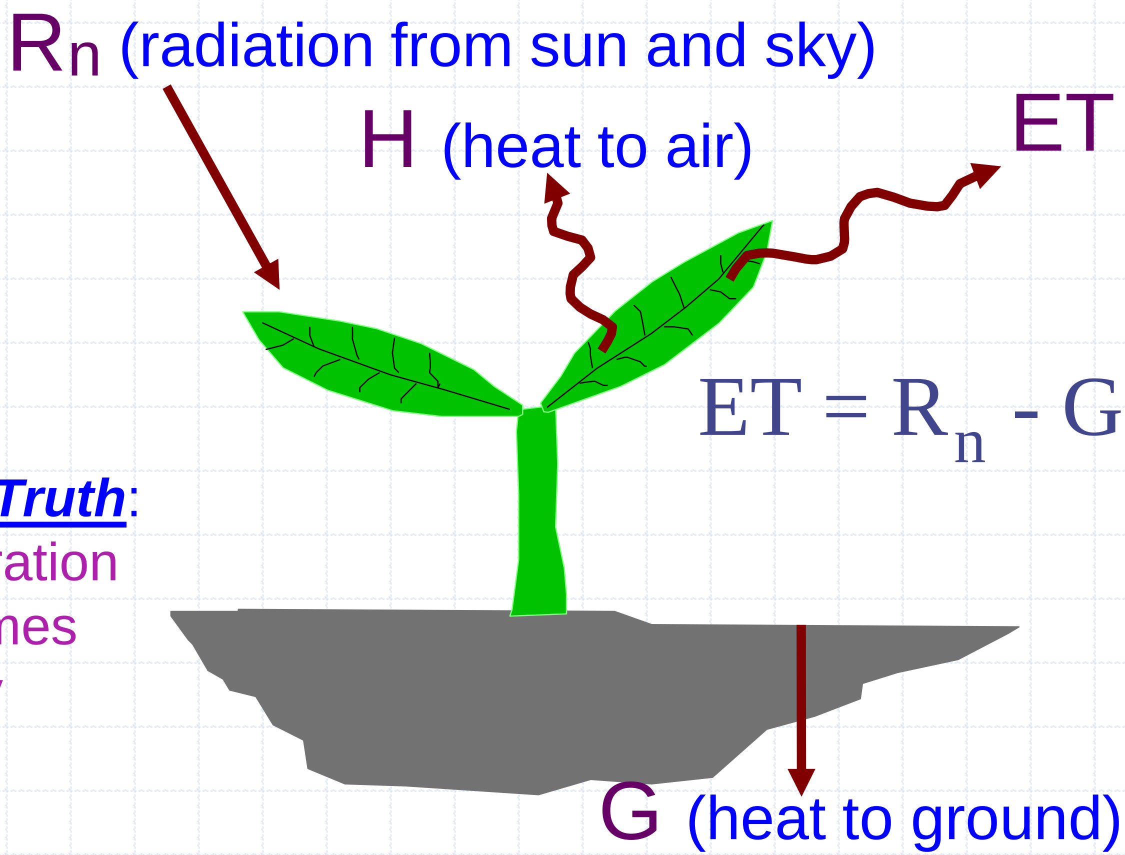


When Energy Balance Matters

- Energy Balance
  - Remember: ET is the water that changes from liquid to water vapor
  - Liquid to vapor conversion requires energy
  - We ‘look’ for the energy used to produce the evaporation
  - **EB components can be derived from the temperature of the surface**

Why use an "Energy balance"?

- ET is calculated as a "residual" of the energy balance



$$ET = R_n - G - H$$

Basic Truth:
Evaporation consumes Energy

Energy balance gives us "actual" ET

Energy Balance can 'see' impacts on ET caused by:

- **water shortage**
- disease
- crop variety
- planting density
- cropping dates
- salinity
- management

- *(these effects can cause the ratio ET / amount of vegetation to vary widely, thus the need to compute ET as a residual of the energy balance)*

Sensible Heat Flux (H) – METRIC model

Advantage:
r_{ah} 'floats' above the surface and is 'free' of z_{oh} and some limitations of a single source approach

$$H = (\rho \times c_p \times dT) / r_{ah}$$

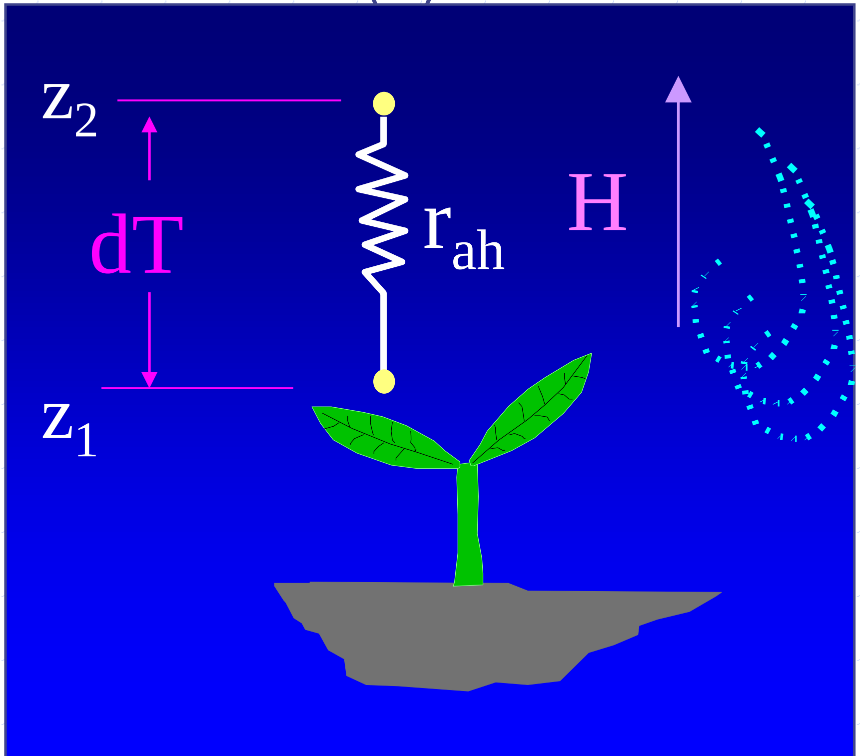
Advantage:
dT is inverse calibrated (simulated) (free of T_{rad} vs. T_{aero} vs. T_{air})

dT = "floating" near surface temperature difference (K)

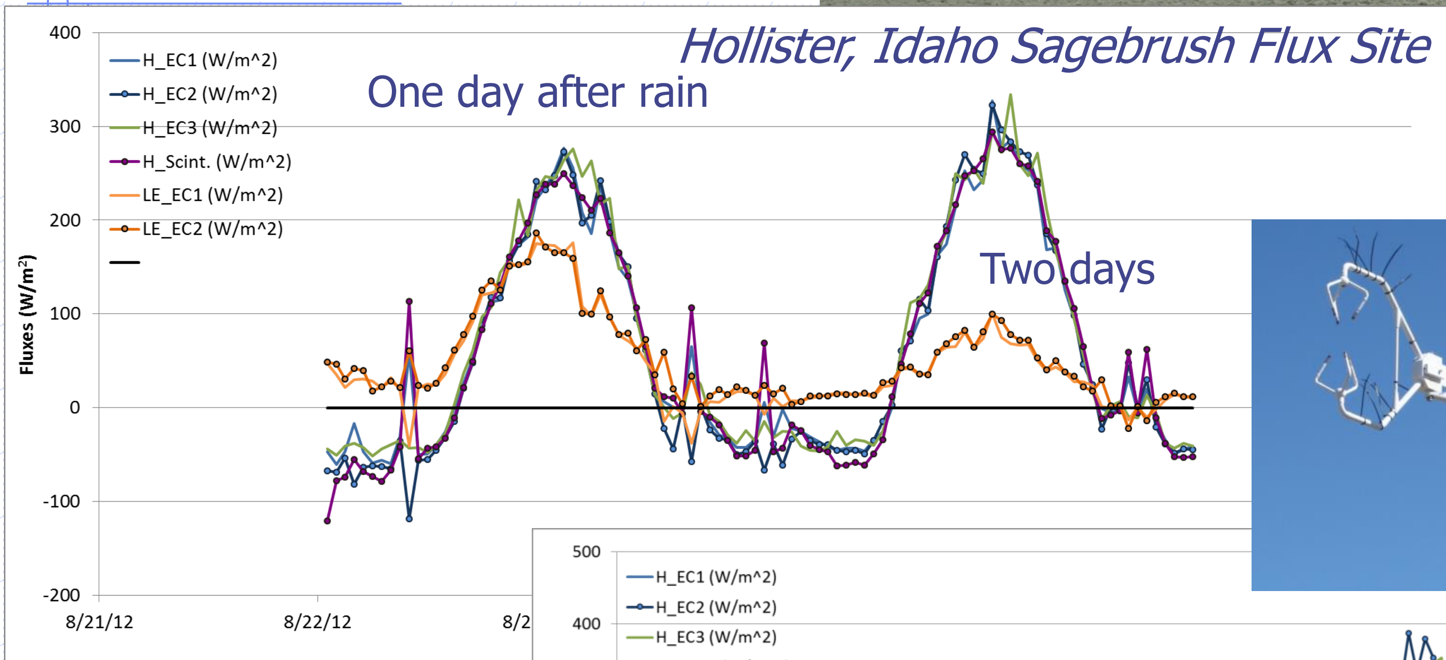
r_{ah} = the aerodynamic resistance from z_1 to z_2

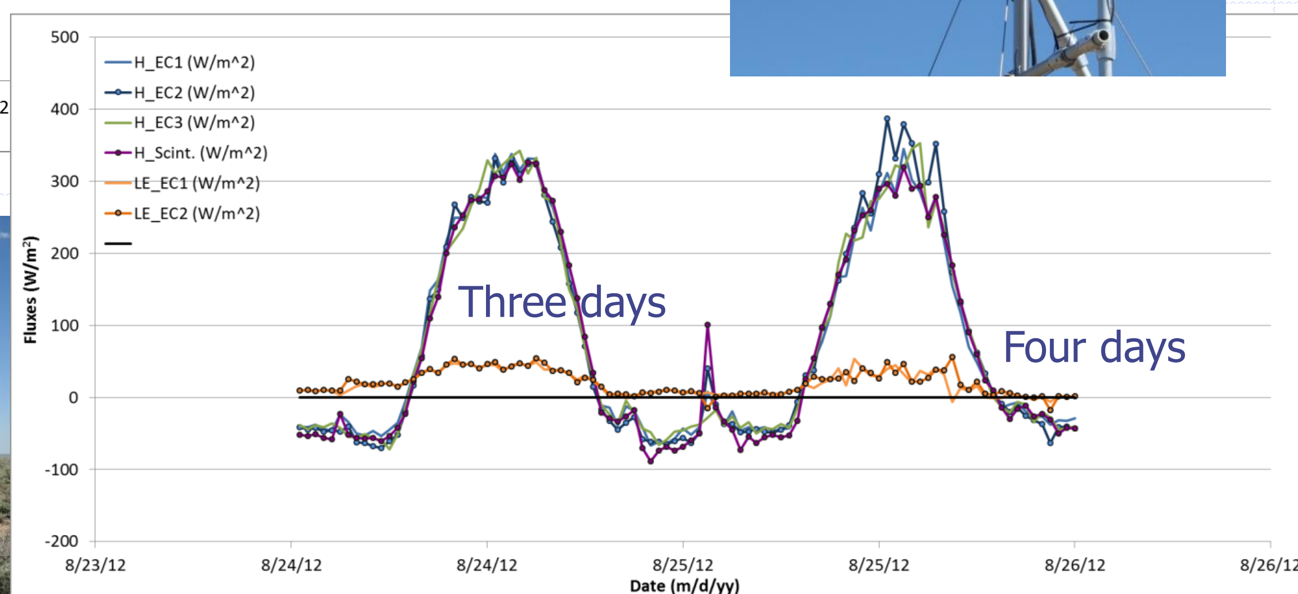
$$r_{ah} = \frac{\ln\left(\frac{z_2}{z_1}\right) - \Psi_{h(z_2)} + \Psi_{h(z_1)}}{u_* \times k}$$

u_* = friction velocity
k = von karmon constant (0.41)

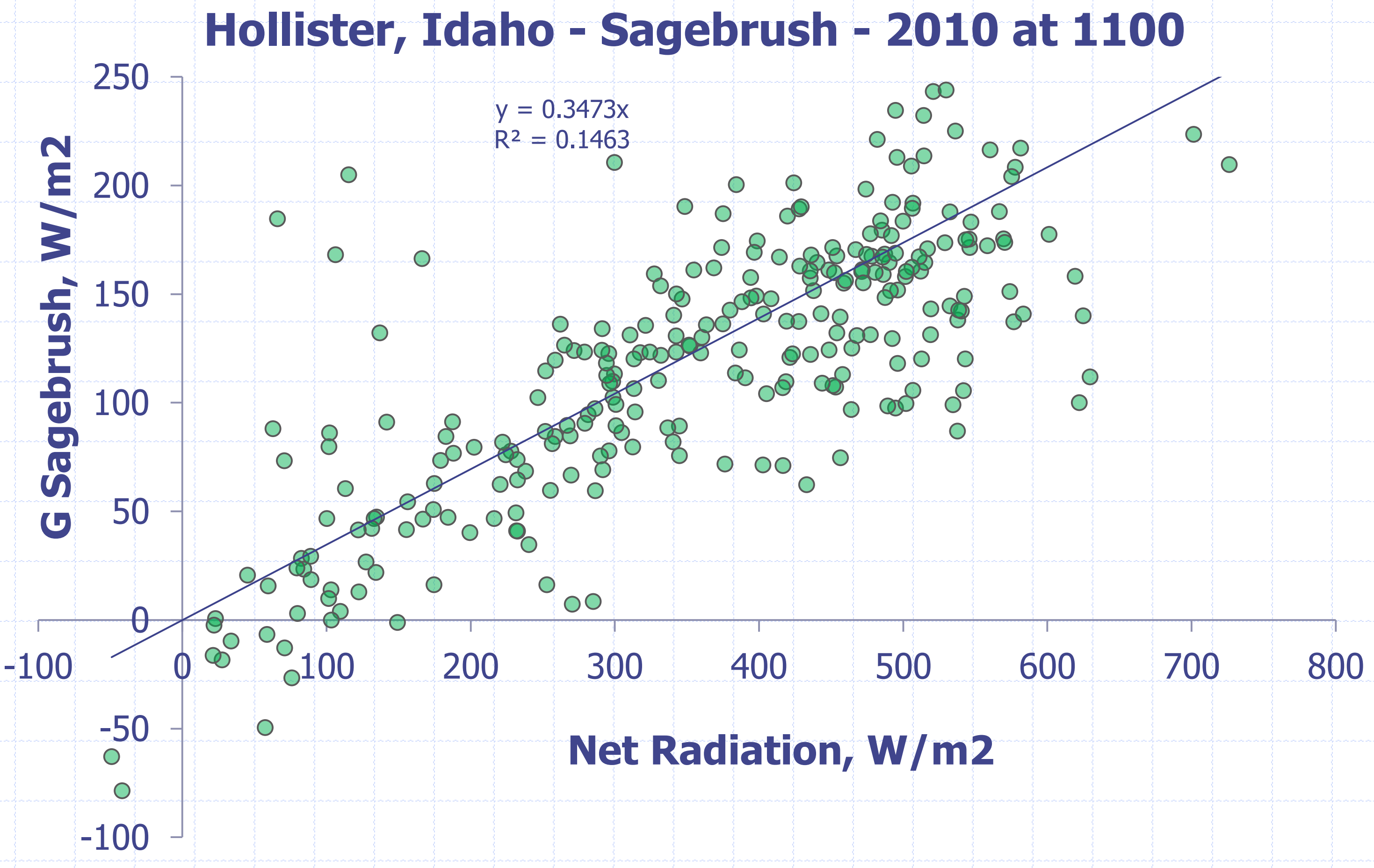


Low levels of ET require high quality surface energy balance





G for water stressed systems can be large and needs to be accounted for



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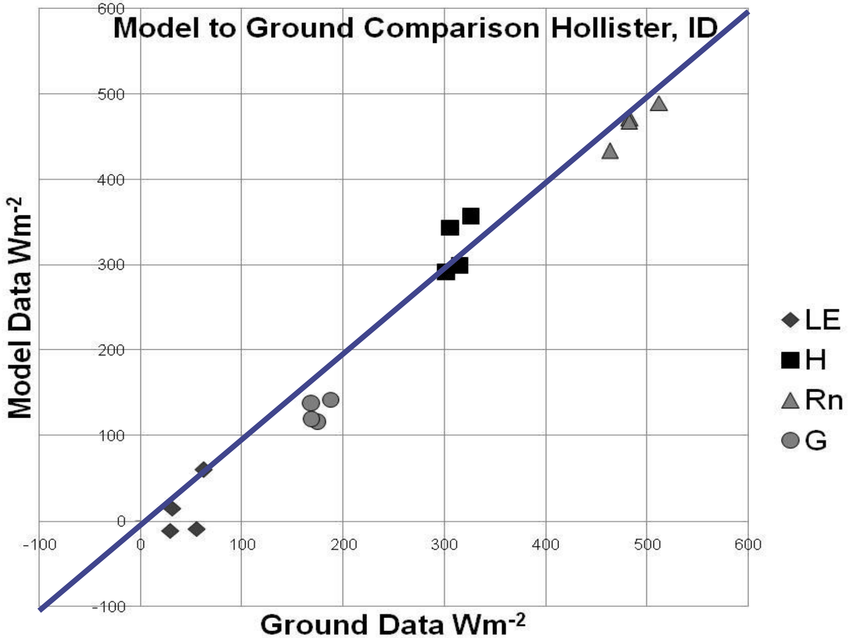
Idaho NSF EPSCoR Flux Sites – Desert Systems



Four Landsat Dates during 2010 – Sagebrush

April – September ET from METRIC

- Comparison of satellite-based surface energy balance (METRIC) with Eddy Covariance for very low ET signal

Hydroclimate

Calibration of METRIC/SEBAL:

$\text{bias}_{Rn\text{-}G} \rightarrow \text{bias}_{H\text{-}cal} \rightarrow \text{bias}_{dT} \rightarrow \text{bias}_{H\text{-}pixel} \cancel{\rightarrow} \text{LE}$

unbiased

The Sensible Heat (H) Function *calibrates around Biases in many of the Energy balance components:*

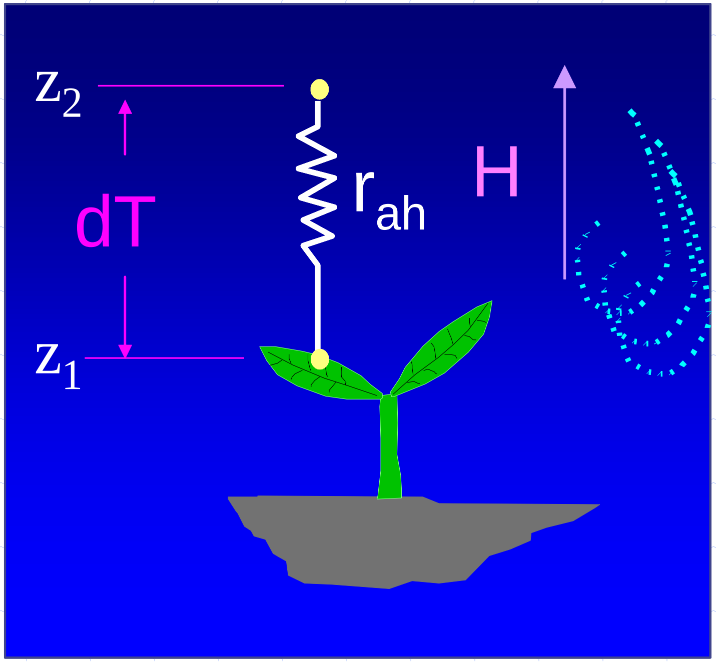
(Biases exist in: net radiation, soil heat flux, aerodynamic stability, aerodynamic roughness, absolute surface temperature, atmospheric correction)

any biases

$H = R_n - G - LE$ *(for calibration)*

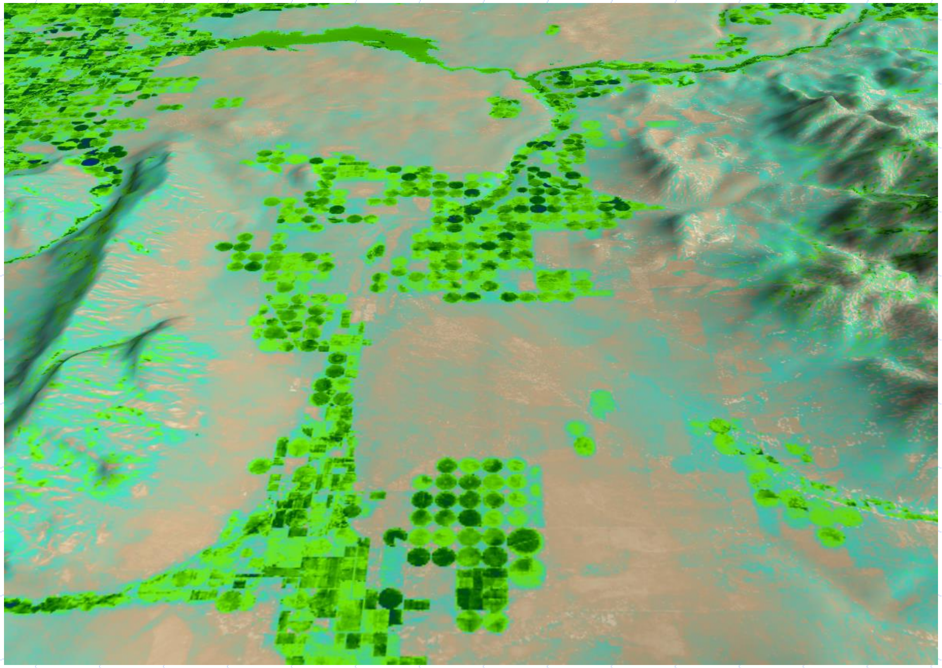
$LE = R_n - G - H$ *(during application)*

Biases cancel out

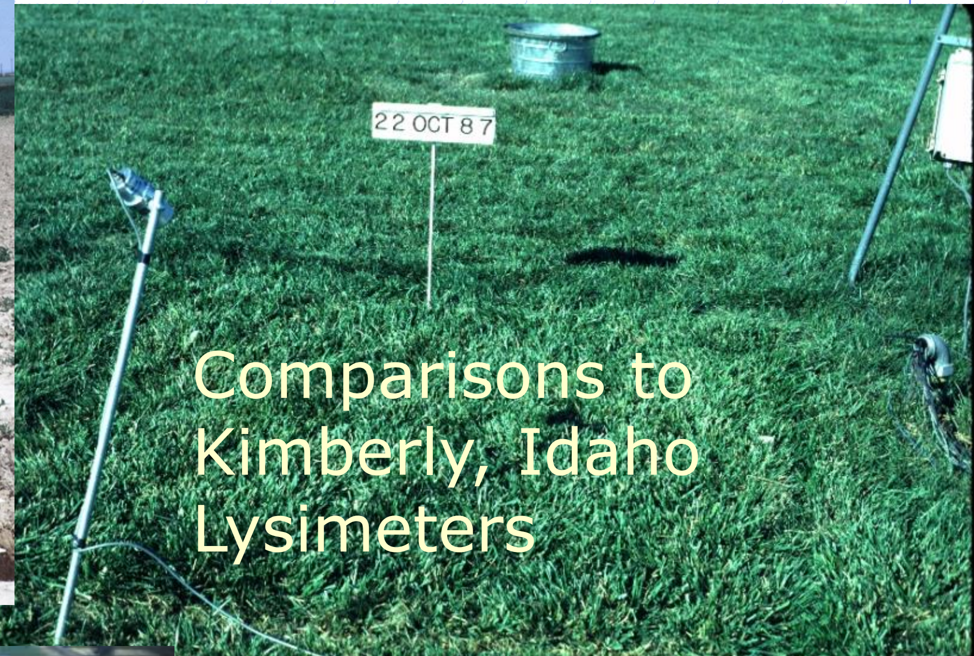


A formula for quantifying spatially and time-variable processes

Accuracy = physics x human effort
+ human review



Comparisons to Kimberly, Idaho Lysimeters



photos courtesy of Dr. J.Wright, USDA-ARS (ret) and R.Allen, Univ. Idaho

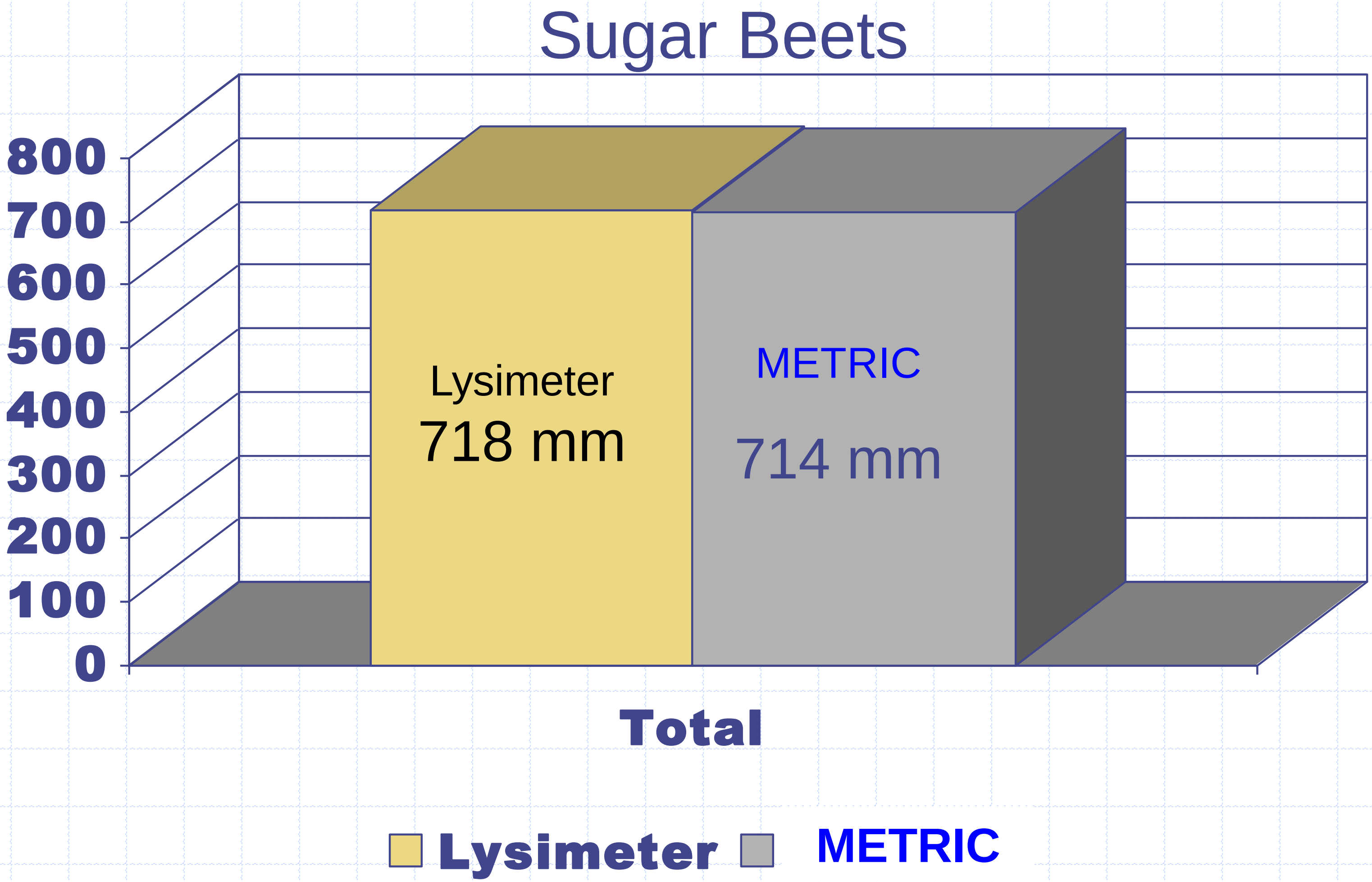
Weighing Lysimeter System at Kimberly, Idaho

Dr. James L. Wright, USDA-ARS

University of Idaho

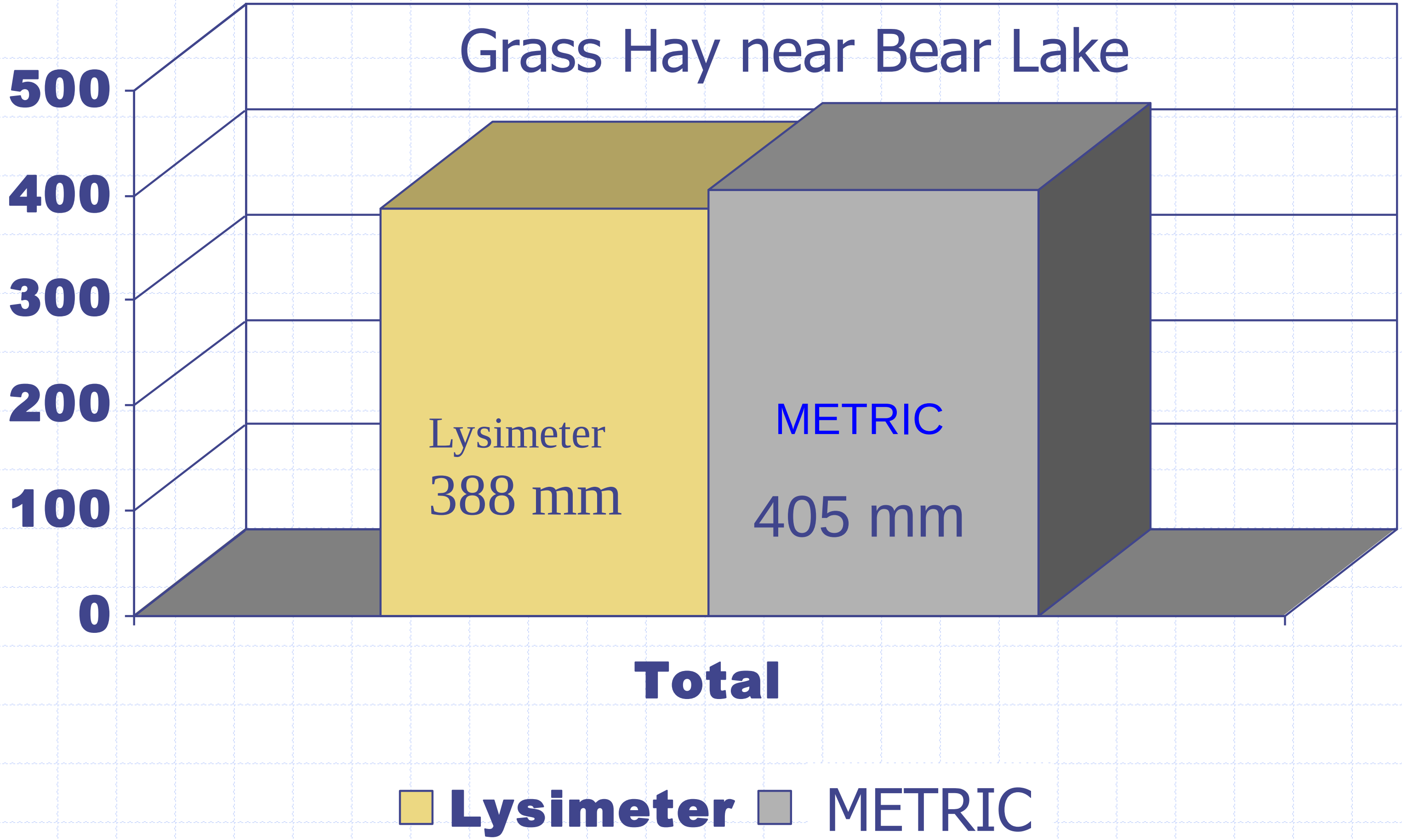
Comparison of Seasonal ET by METRIC™ with Lysimeter

ET (mm) - April-Sept., *Kimberly, 1989*



Comparison of Seasonal ET by $METRIC_{2000}$ with Lysimeter

ET (mm) - July-Oct., *Montpelier, ID 1985*



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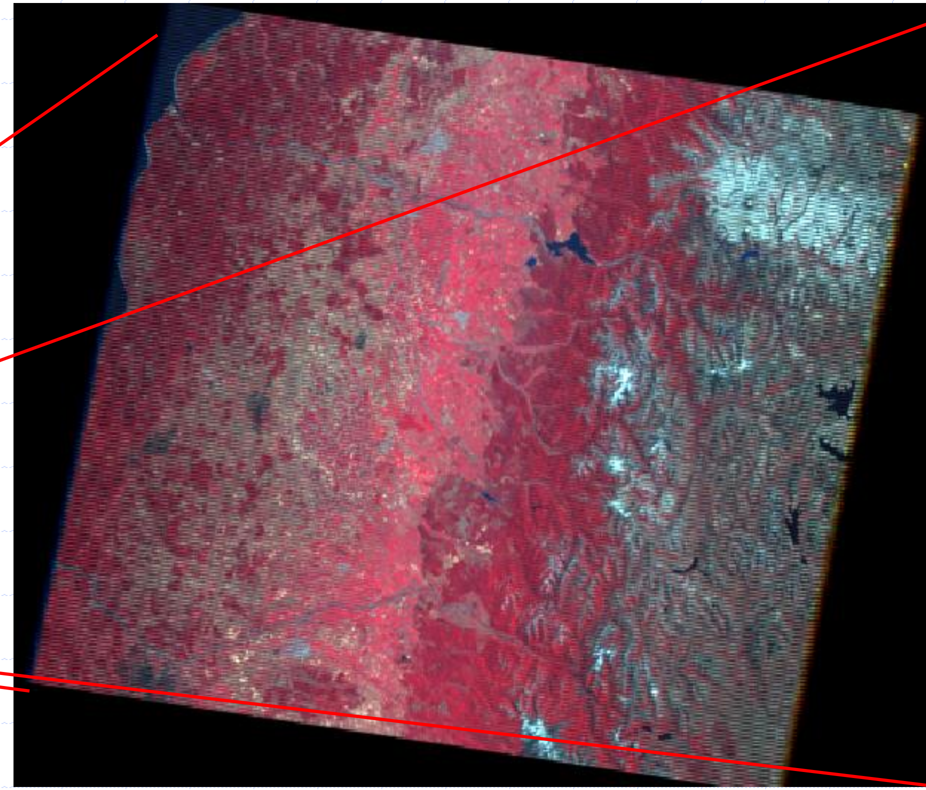
Olives in Chile



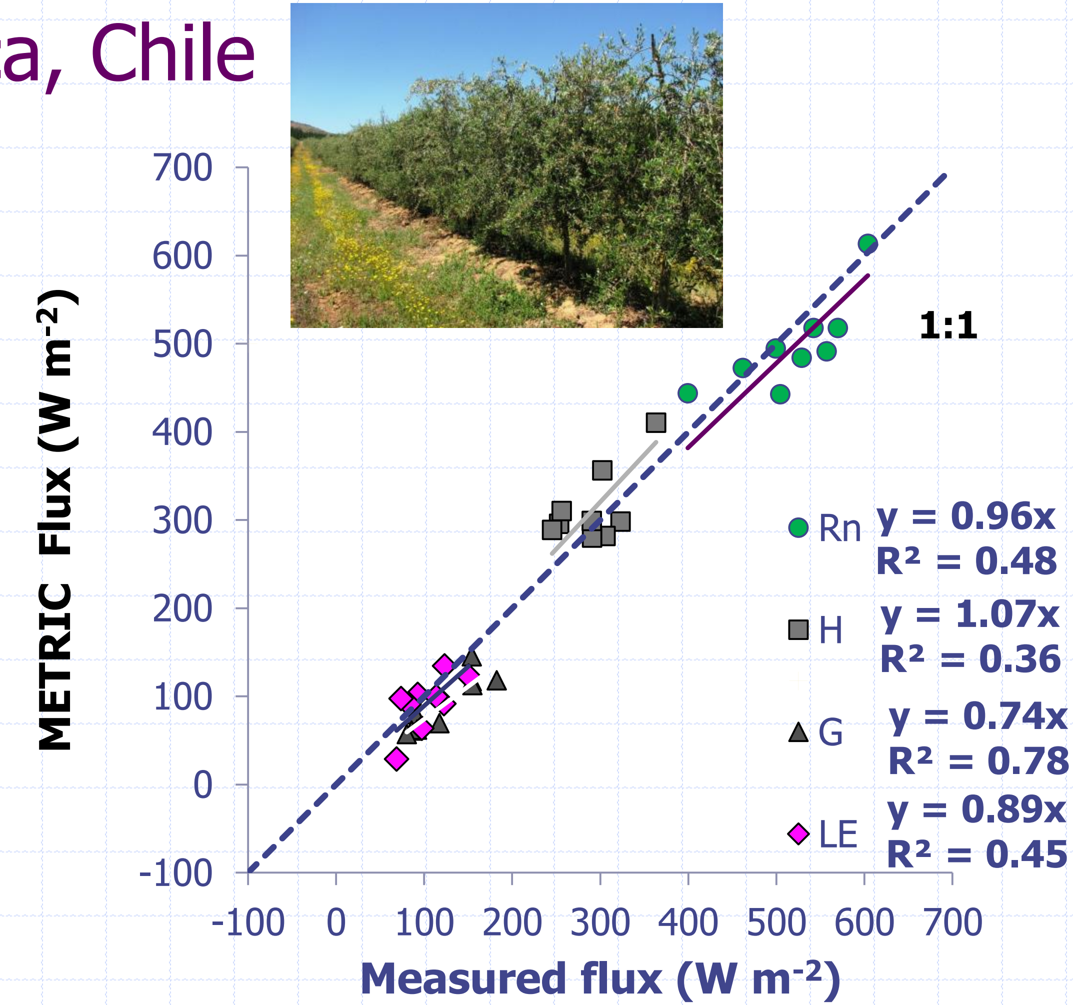
Study area is in the center of Chile

Path 233, Row 85, Landsat 7 processing (2011 & 2012)

Data by Dr. Samuel Ortega, Univ. Talca, Chile, collaboration with Dr. A. Kilic, Univ. Nebraska

Chile

METRIC vs. Ground Measurements – Olive Orchard near Talca, Chile



New olive production in central Chile with relatively dense tree spacing.

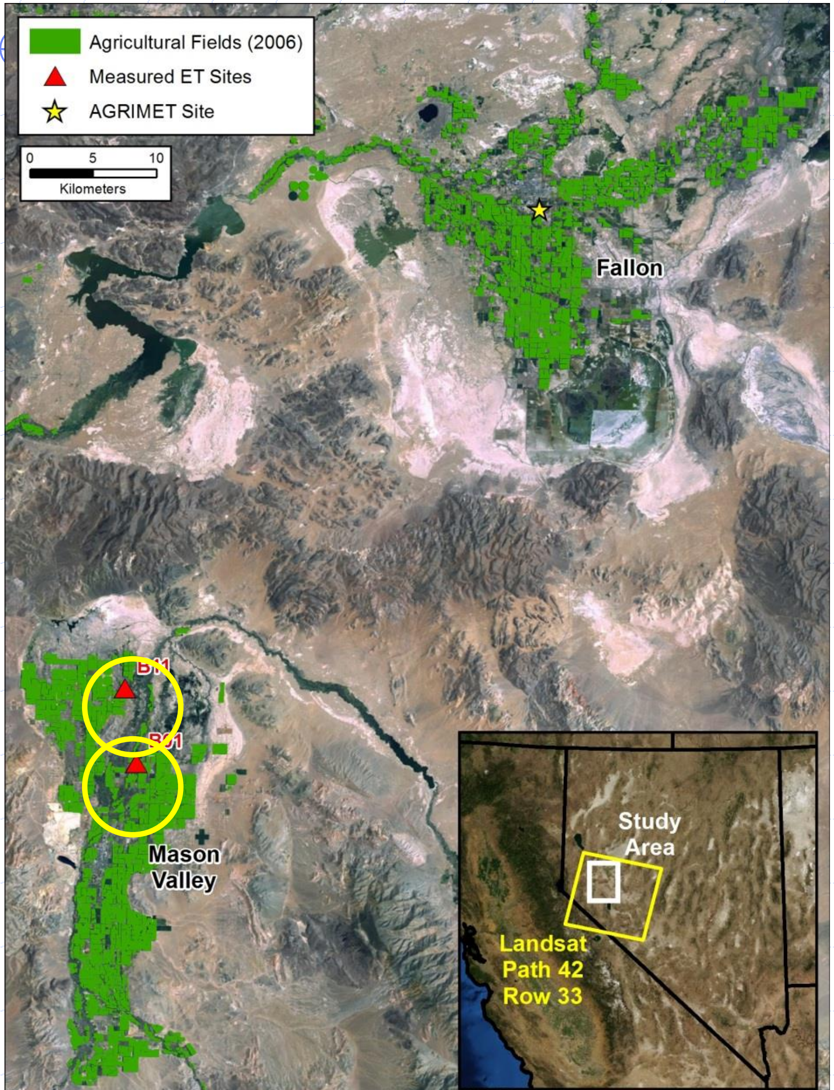
ET fluxes measured using an eddy covariance system mounted above the crop.

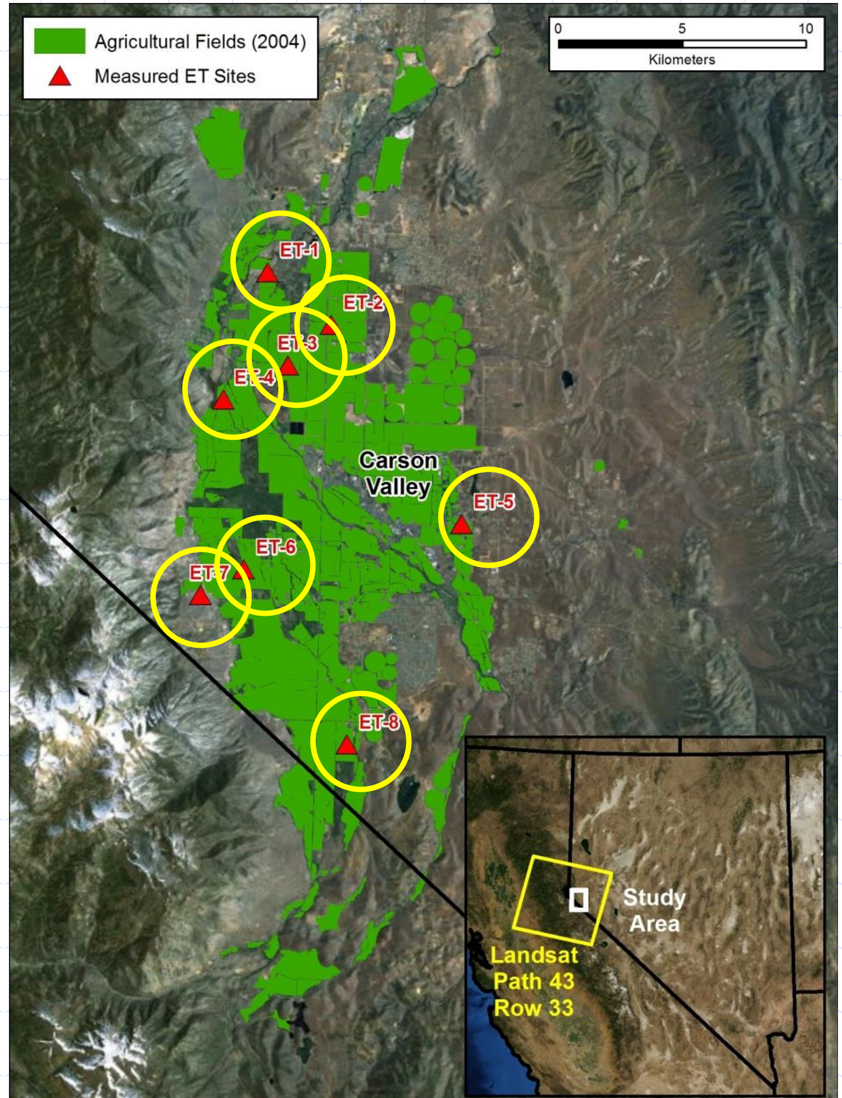
Analyses by Samuel Orlando Ortega Salazar, with with A. Kilic, Univ. Nebraska

Nevada

compiled by Dr. Justin Huntington, DRI

Blind Comparison of METRIC Seasonal ET to Measured ET – Desert Research Institute





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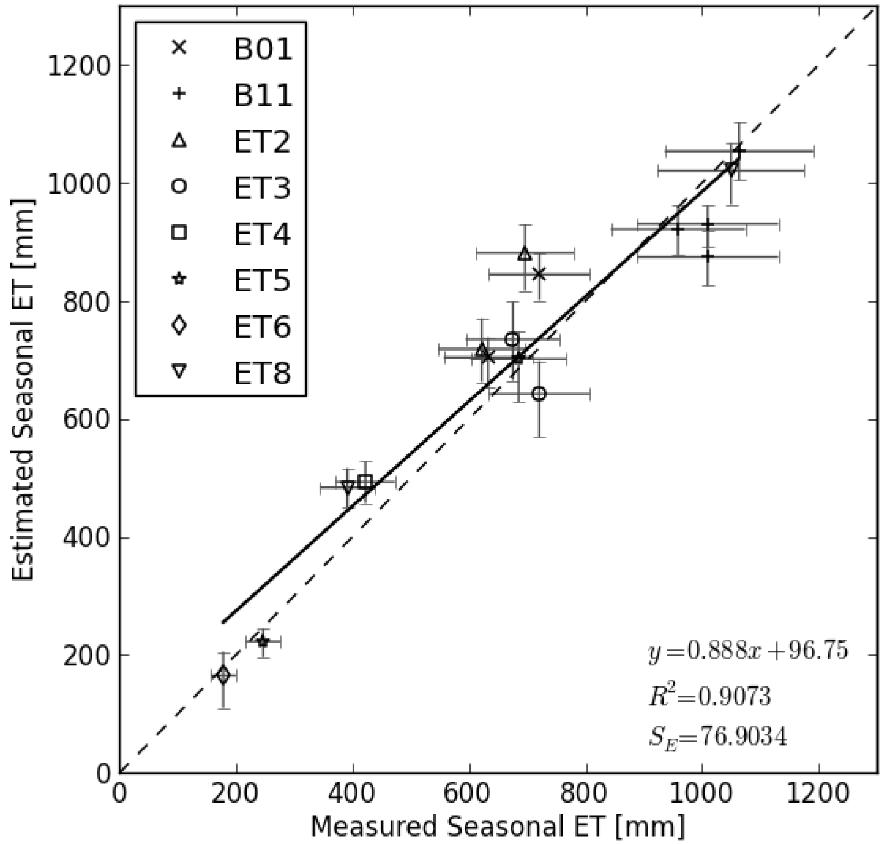
Ground measurement data by USGS

Nevada

Blind Comparison of METRIC Seasonal ET to Measured ET



Ground data by USGS

- Whiskers on X = +/- 12% USGS estimated uncertainty in measured Bowen ratio/eddy ET
- Whiskers on Y = +/- 95% confidence interval of 100 Monte Carlo METRIC ET estimates

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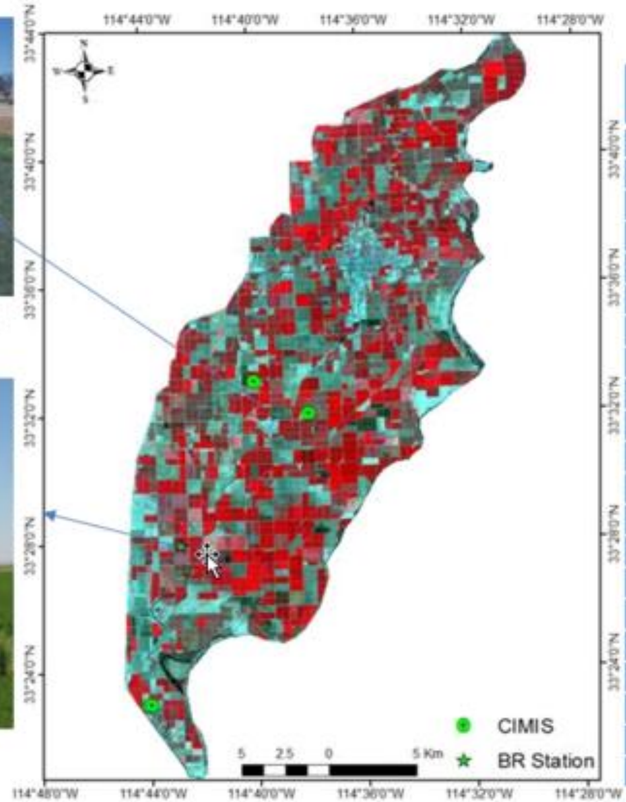
Dr. Justin Huntington, DRI

"Blind" Intercomparison of Leading ET models – 2014 – SE California

Site 1: Palo Verde Irrigation District (PVID)

CIMIS Weather Station , Blythe NE # 135

Full surface energy balance flux measurements based on Bowen Ratio Station



False color RGB , NIR-Red-Green Landsat 5 image during DOY 131, May 10, 2008

List of Landsat 5 scenes used

No.	Date (2008)	DOY (2008)	Path	Raw
1	19-Jan	19	38	37
2	11-Feb	42	39	37
3	27-Feb	58	39	37
4	07-Mar	67	38	37
5	23-Mar	83	38	37
6	08-Apr	99	38	37
7	24-Apr	115	38	37
8	10-May	131	38	37
9	17-May	138	39	37
10	26-May	147	38	37
11	11-Jun	163	38	37
12	18-Jun	170	39	37
13	13-Jul	195	38	37
14	29-Jul	211	38	37
15	05-Aug	218	39	37
16	21-Aug	234	39	37
17	15-Sep	259	38	37
18	01-Oct	275	38	37
19	17-Oct	291	38	37
20	09-Nov	314	39	37
21	18-Nov	323	38	37

UtahState University

USGS science for a changing world

University of Idaho

“Blind” Intercomparison of Leading ET model

Summ

Individual
– vs. Grou

	RMSE	BIAS
Measured		
	1.5	-0.2
	2.7	-2.5
METRIC	0.9	-0.1
	1.3	-0.8
	2.1	-1.7

Seasonal Water Balance

Water balance Component	Depth (mm/year)			METRIC			
Precipitation	71	71	71	71	71	71	71
Inflow Main Canal	2479	2479	2479	2479	2479	2479	2479
Total Inflow	2550	2550	2550	2550	2550	2550	2550
Canal Spills	284	284	284	284	284	284	284
Drainage	998	998	998	998	998	998	998
ET	**(1000)**		**956**	**1223**	**952**	**X**	
Total Outflow	(2282)		2238	2505	2234	X	
Inflow- Outflow	(268)		312 (-12.2%)	34 (-1.8%)	316 (-12.4%)	X	

Estimates by METRIC were < 2% for both individual field and entire district

Other applications where effort and accuracy matters

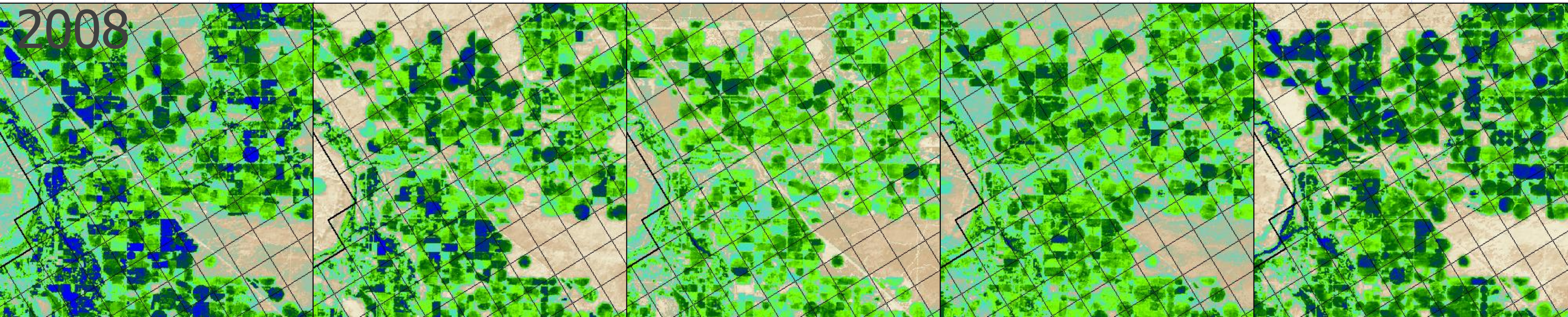
Idaho

Eastern Snake Plain Aquifer Model

METRIC ET data:

- Have provided more accurate calibration of the groundwater model
- Improved accuracy of depletions and recharge estimates
- Shows long term trends and annual variation in ET

1996 2000 2002 2006 2008



Idaho Clear Springs Foods Water Call

Idaho Business News

Water curtailment ordered in Magic Valley

POSTED: 11:13 MDT Thursday, July 23, 2009

by **IBR Staff**

Idaho Department of Water Resources Interim Director Gary Spackman on July 22 issued a **curtailment order** to about 250 holders of 315 junior water rights in south central Idaho's Magic Valley. The curtailment order is part of a continuing response to a water delivery call made in 2005 by senior water right holder Clear Springs Foods.

State goes ahead with first large-scale well closure of more than 300 water rights in M.V.

7/31/2009

Water districts have limited options, could file a stay

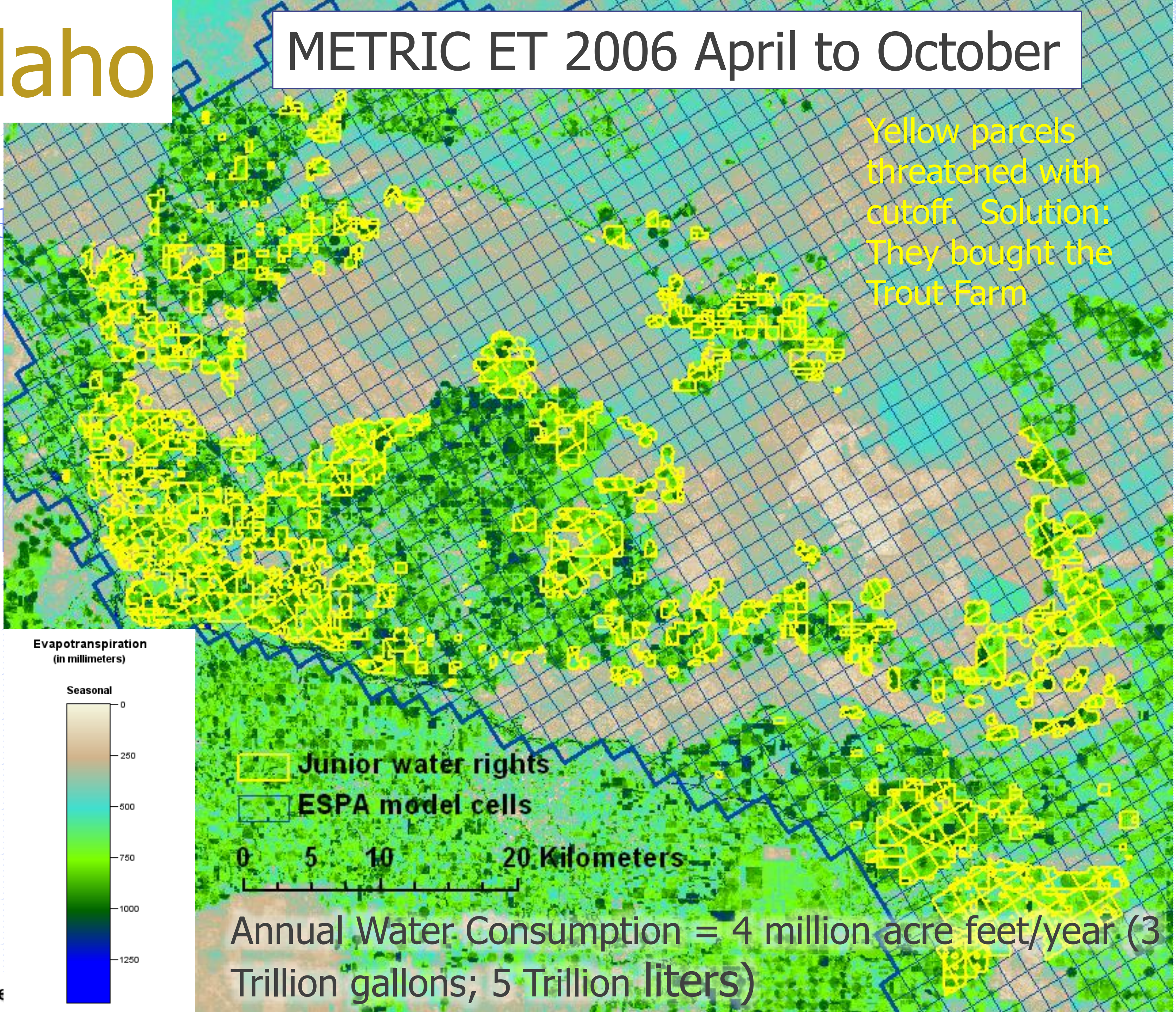
By Nate Poppino

Times-News writer

The Idaho Department of Water Resources will go forward this morning with a plan to shut off more than 300 water rights irrigating just less than 9,000 acres of Magic Valley farmland, the first wide-scale well curtailment to actually be carried out by the state.

Idaho

METRIC ET 2006 April to October

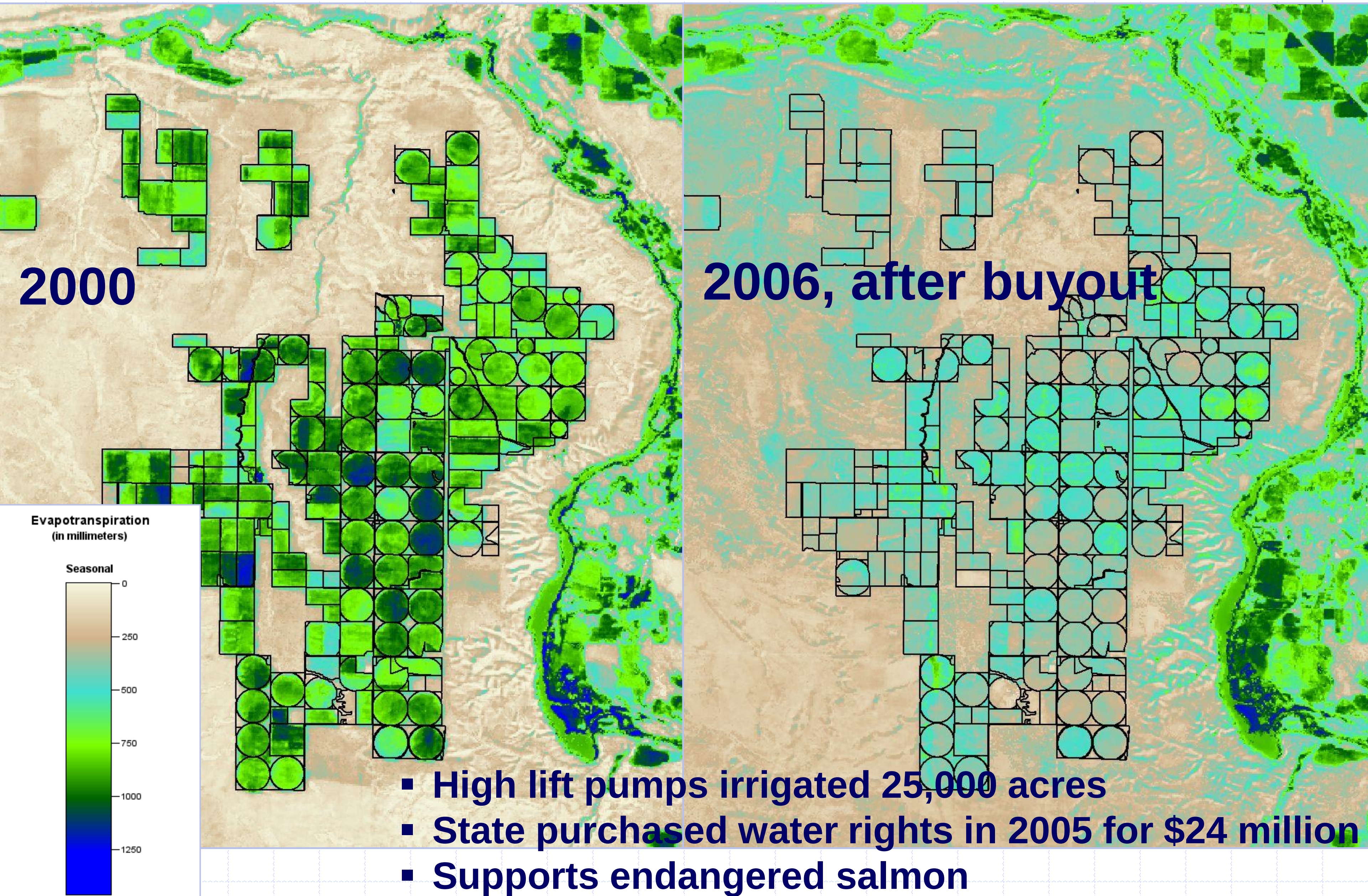


Yellow parcels threatened with cutoff. Solution: They bought the Trout Farm

Annual Water Consumption = 4 million acre feet/year (3 Trillion gallons; 5 Trillion liters)

Idaho

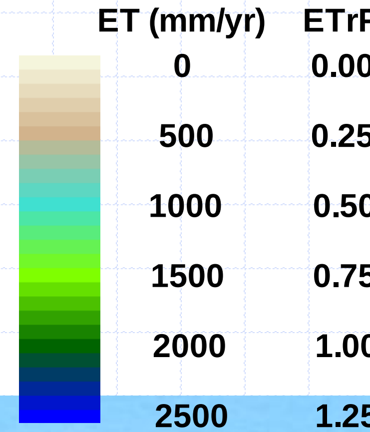
Bell Rapids Irrigation Project, Idaho: Seasonal ET



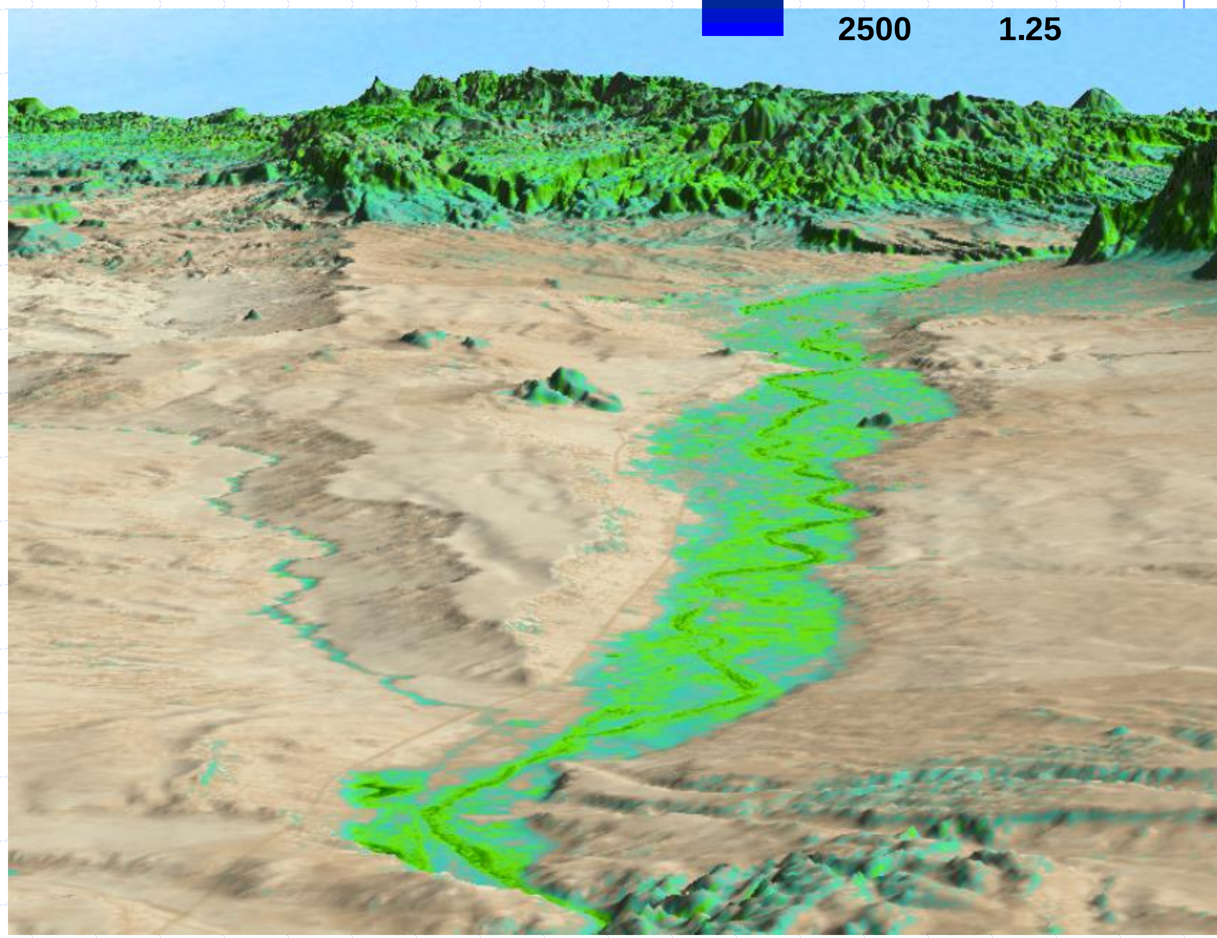
- High lift pumps irrigated 25,000 acres
- State purchased water rights in 2005 for $24 million
- Supports endangered salmon

New Mexico

Rio Grande of New Mexico



- Pueblo *(native American)* water rights dating to Coronado in 1500’s
- Invasion of salt cedar
- Does increased pecan production increase ET from irrigated agriculture?

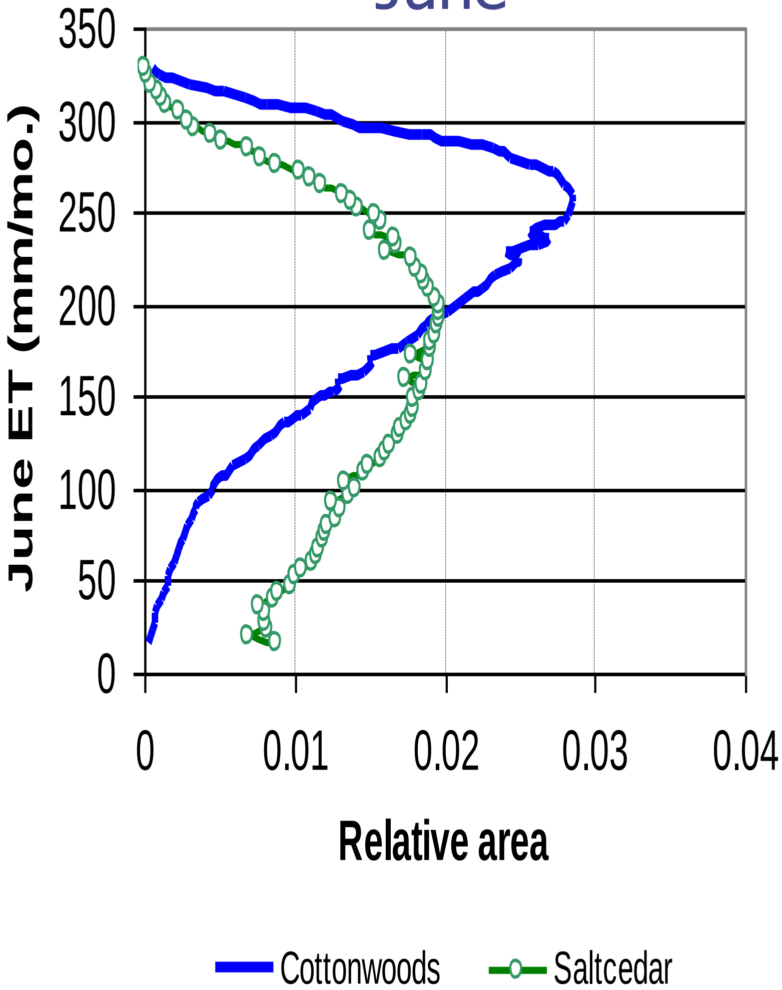


New Mexico

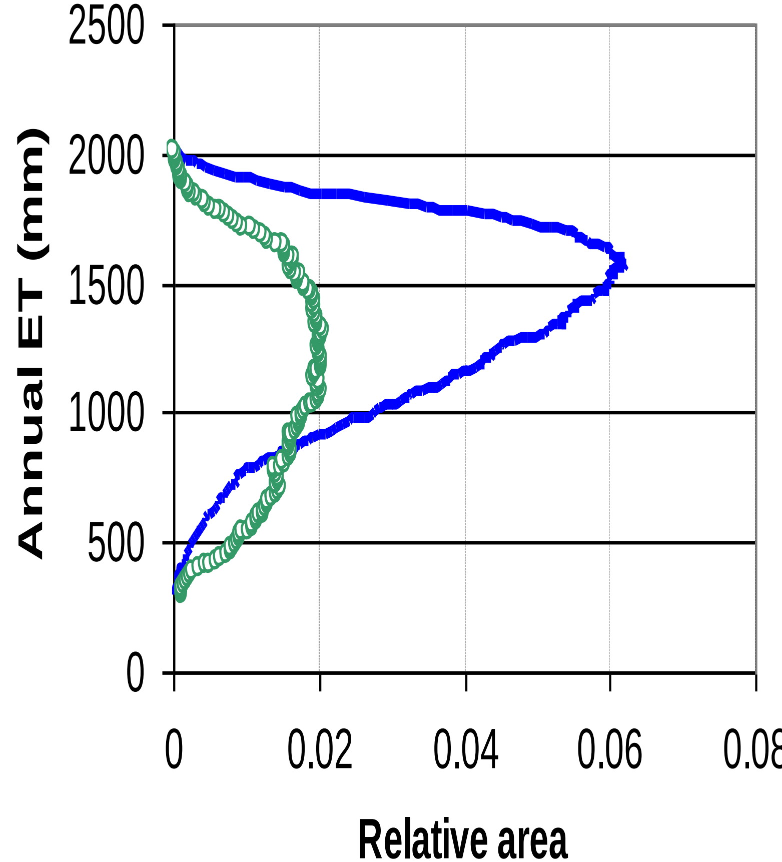
Frequency Distribution of ET

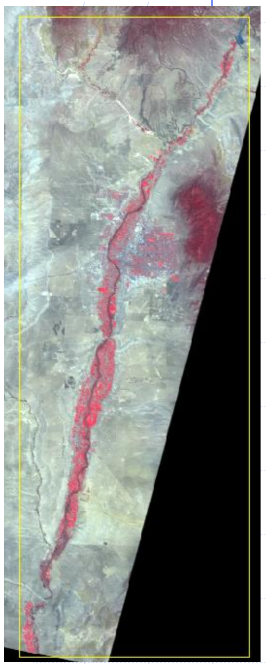
15,000 acres of cottonwood and salt cedar

June



Annual

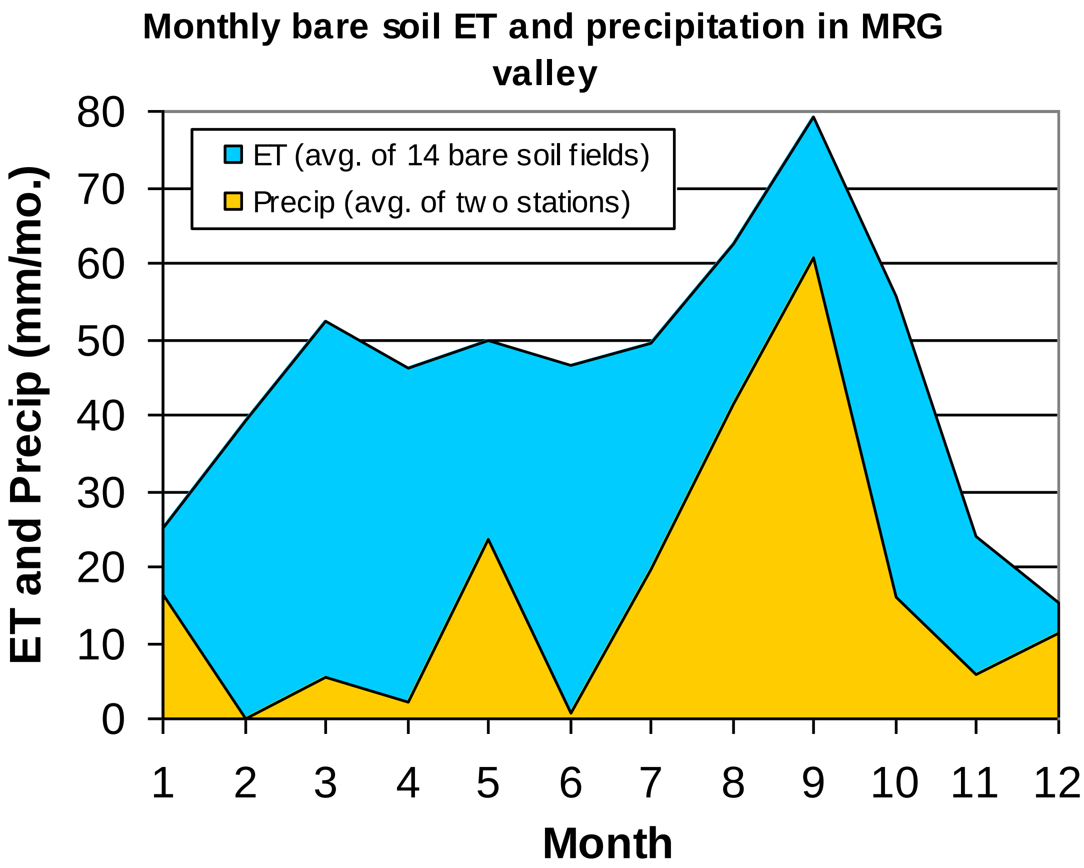




Tasumi and Allen, 2006

Cottonwoods
Saltcedar

With Thermal Imaging, we can see important evaporation from wet soil – for example from high water tables

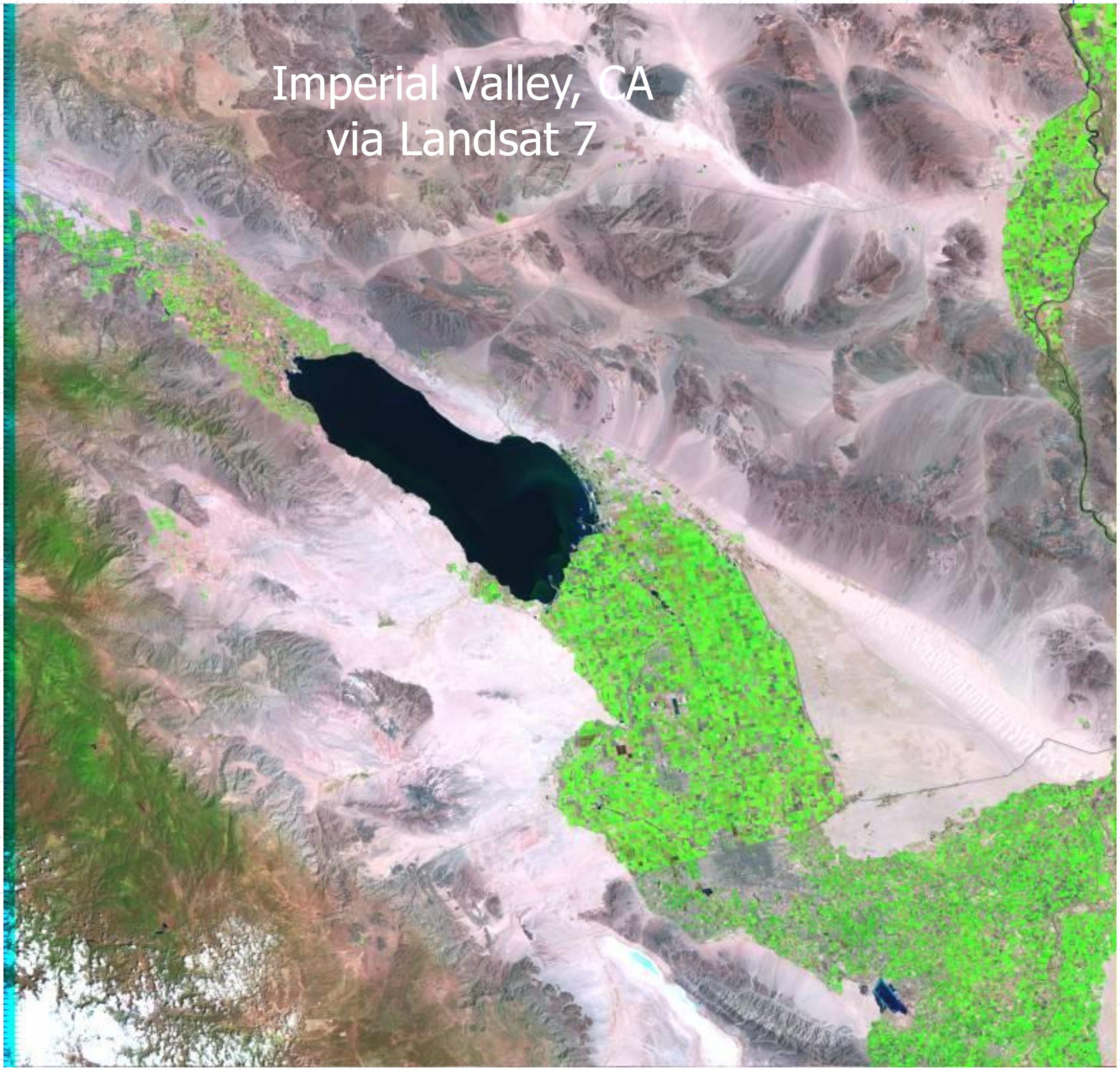


Evaporation during 2002 from continuously bare areas along the ***Middle Rio Grande*** *of NM contrasted with precipitation*

California

Imperial Valley

- ~15% of traditional water supply to agriculture will now flow to San Diego/ Los Angeles
- What is the impact on agriculture, water consumption and on the Salton Sea?



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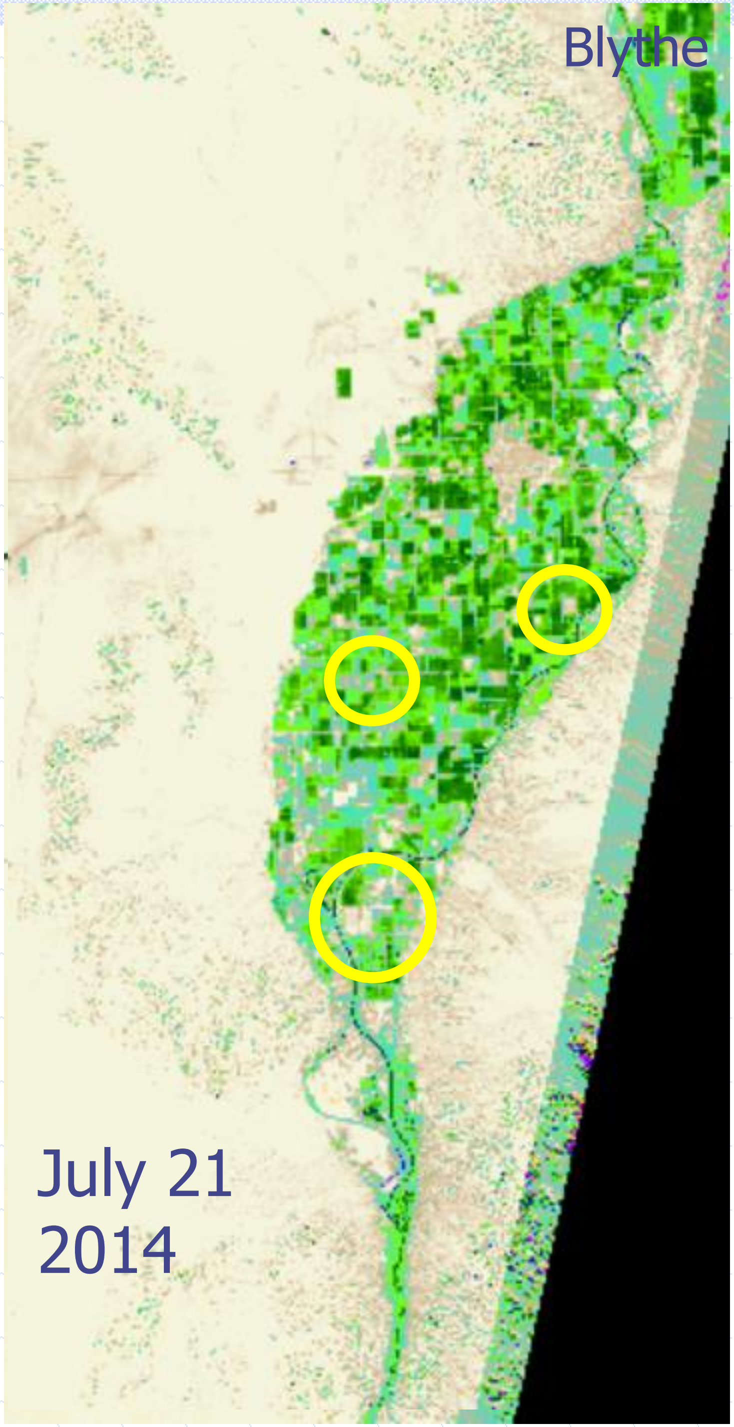
Fallowed Fields in 2014

- Reduction of ET ‘should’ reduce to nearly zero (if little rainfall)
- Transition of alfalfa fields is notable
- Cities are able to document reduction of agricultural ET and compliance with Colorado River Compact



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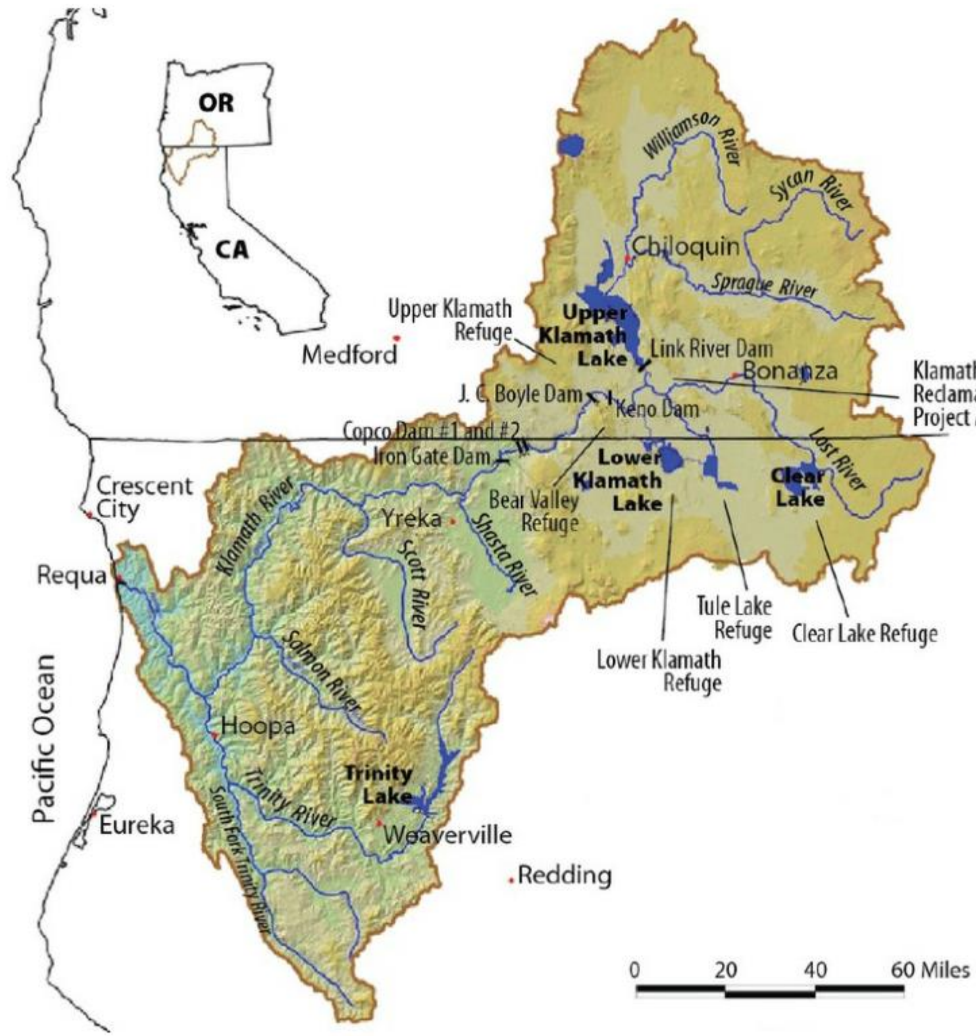
Background- The Klamath River Basin

- Home to many diverse species of wildlife
- Economically and culturally diverse rural communities
- Ecompassing over 12,000 square miles, about the size of the state of Maryland.
- The Karuk, Yurok, and Klamath Tribes still harvest salmon and c'wam from the river for cultural and subsistence purposes
- Family farmers and ranchers use the river for irrigation of diverse crops
- Coastal commercial fishing families depend on Klamath salmon for their living
- Bitter conflicts have emerged between Tribal, agricultural, and commercial fishing communities
- Klamath Tribes were granted senior water rights (may 2013) for large portions of the Upper Basin
- This led to large scale water shut offs necessary to protect Klamath Tribal fisheries



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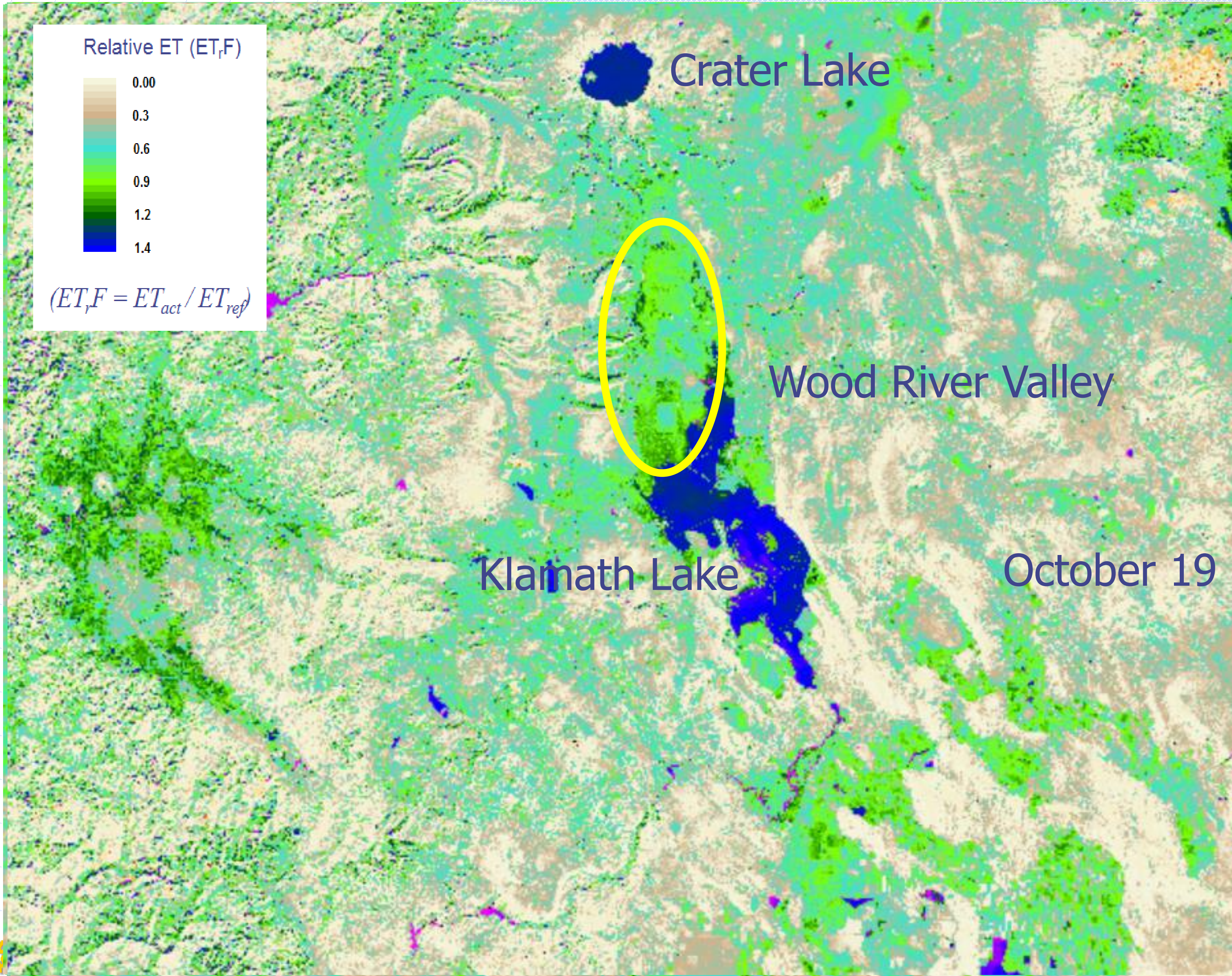
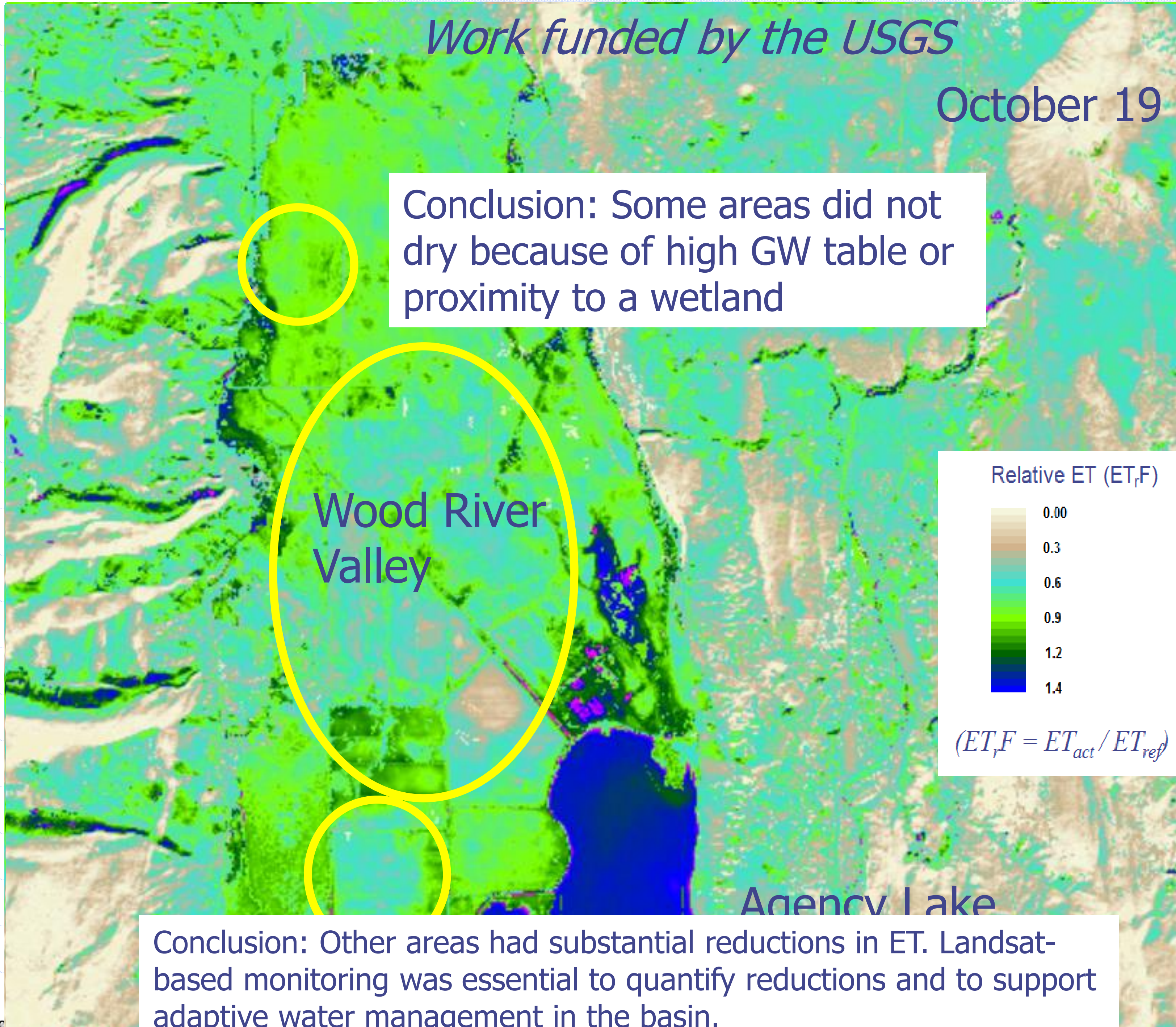


Relative ET (ET_rF)
0.00
0.3
0.6
0.9
1.2
1.4
$(ET_rF = ET_{act} / ET_{ref})$
Crater Lake
Wood River Valley
Klamath Lake
October 19

Work funded by the USGS

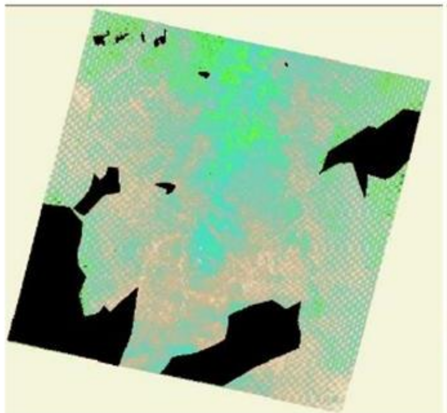


Conclusion: Some areas did not dry because of high GW table or proximity to a wetland

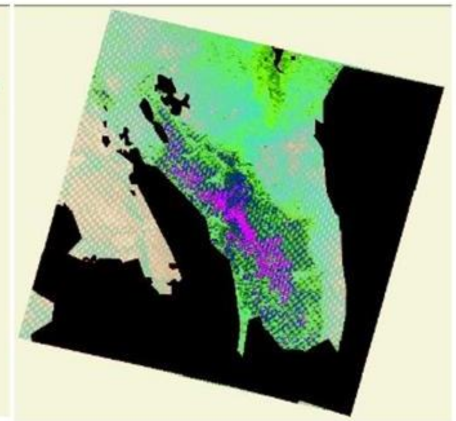
Conclusion: Other areas had substantial reductions in ET. Landsat-based monitoring was essential to quantify reductions and to support adaptive water management in the basin.

Of course, images can be plagued with Clouds

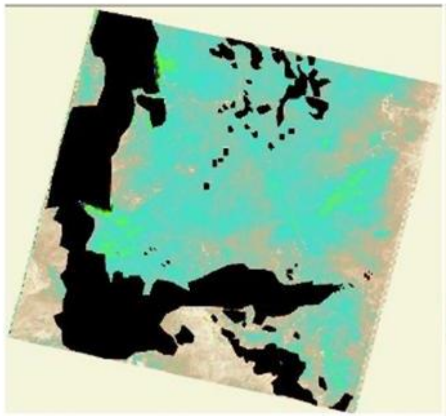
04-16-04



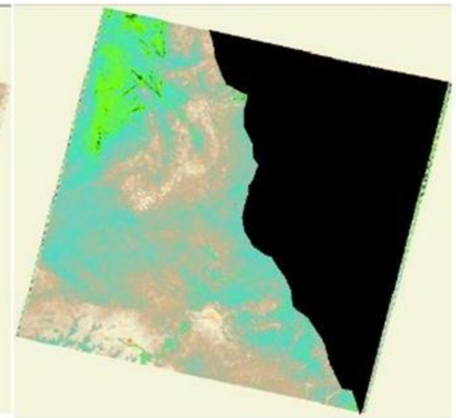
04-23-04



04-24-04

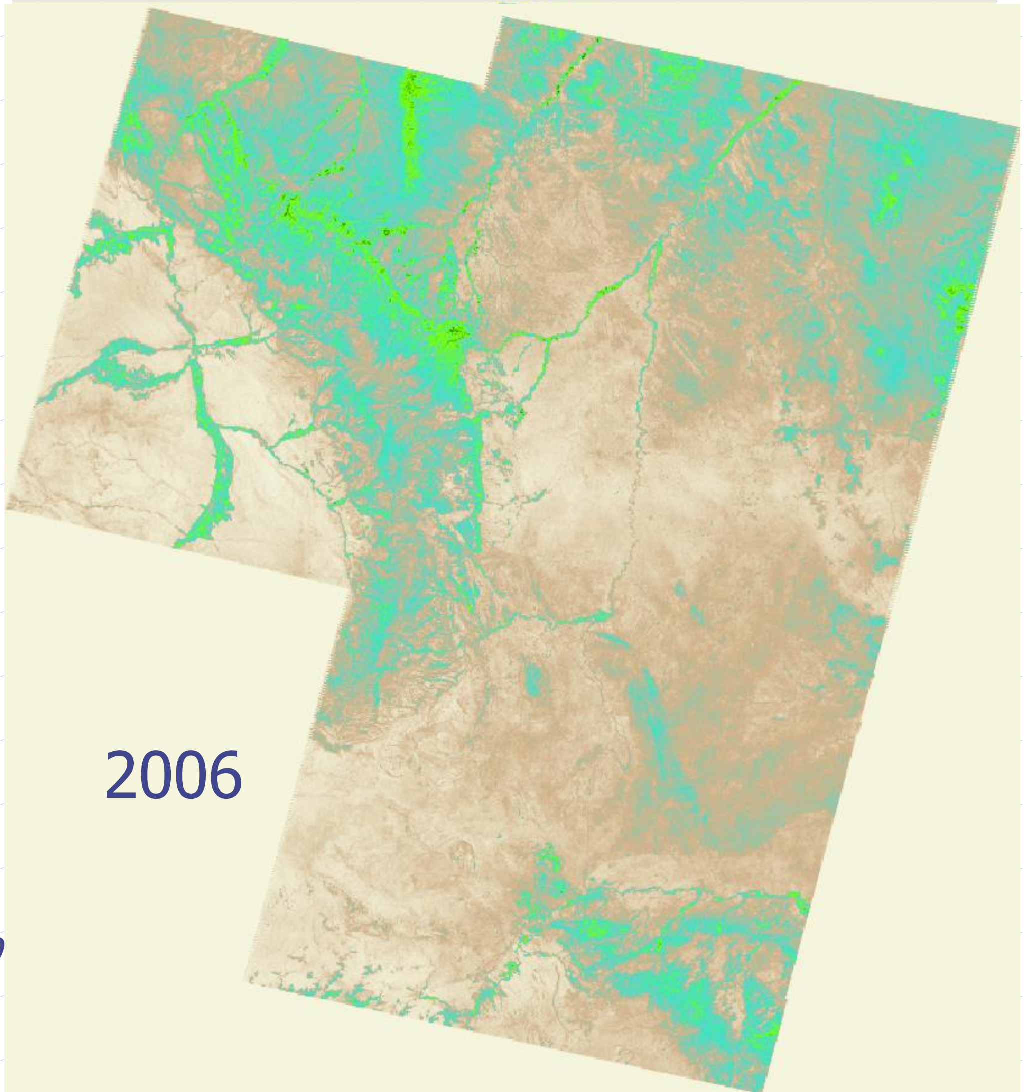


05-10-04

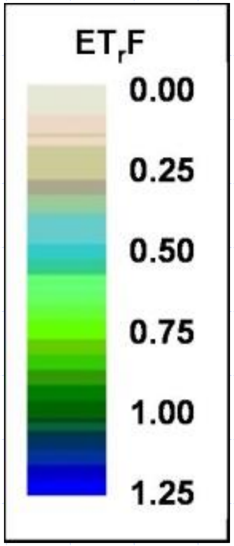


north-central Wyoming

ET from the north Wyoming Region for Years 2004 and 2006 following Time Integration between Landsat images and Mitigation for Clouds



Accurate seasonal ET does not come easy due to the lack of Landsats

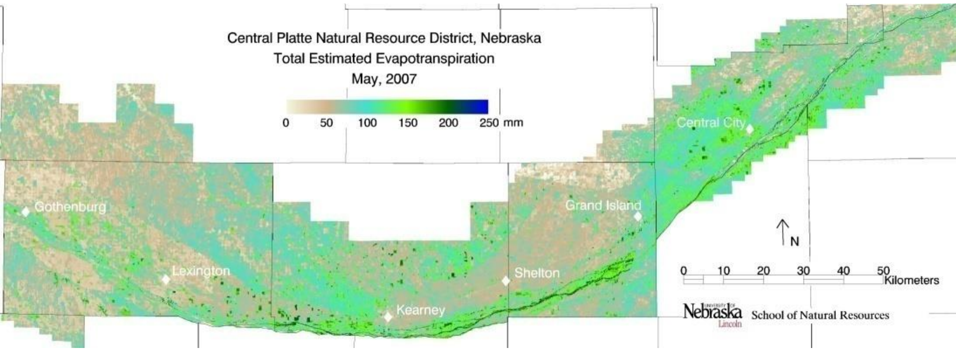


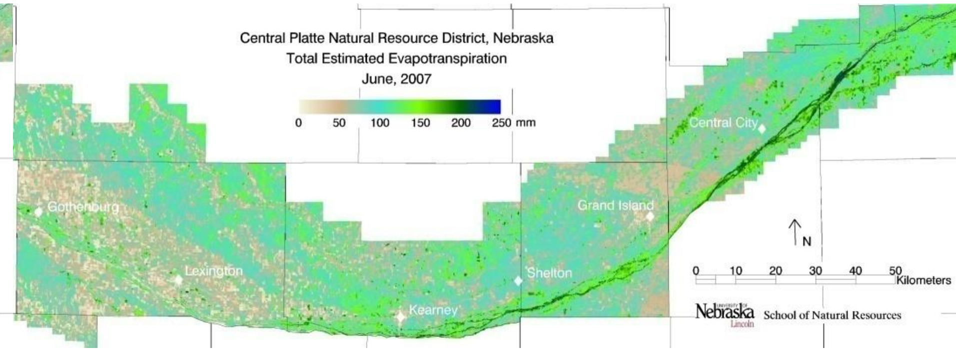
Kelly and Allen, 2009

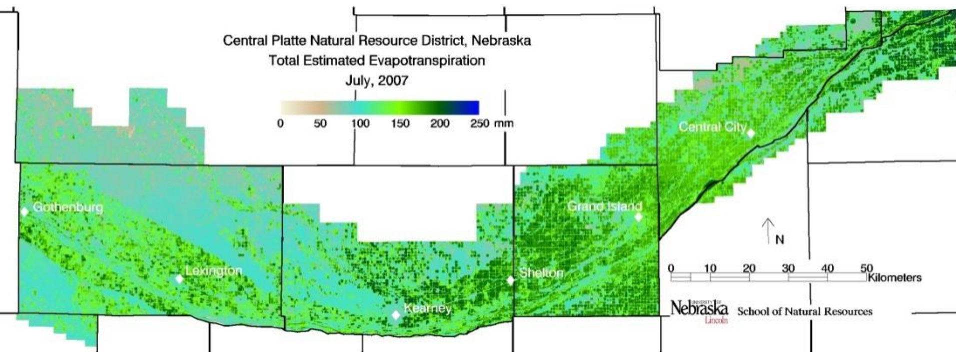
University of Idaho

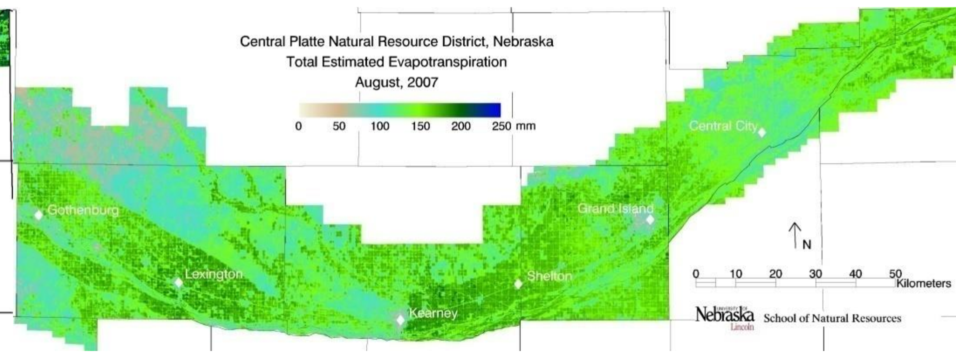
Nebraska

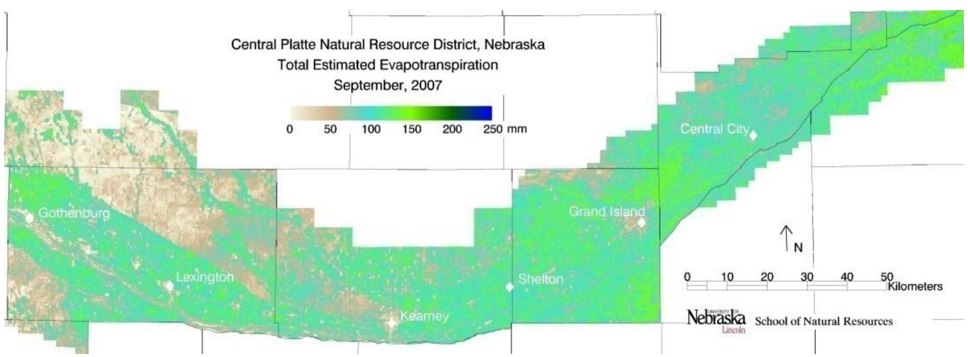
Central Platte Natural Resource District
--- *Management of the Ogallala Aquifer*











Monthly ET

Dr. Ayse Kilic, UNL

CURRENT VENTURE:

EVAPOTRANSPIRATION MODELING TOOL AT LANDSAT RESOLUTION ON GOOGLE EARTH ENGINE --- EEFLUX

EEFlux Development Team

Ayse Kilic – University of Nebraska -- Professor and Presenter, *Member of Landsat Science Team*

Justin Huntington – Desert Research Institute – Professor, *Member Landsat Science Team*

Rick Allen -- University of Idaho – Professor, *Member of Landsat Science Team*

Babu Kamble – University of Nebraska – Developer

Charles Morton – Desert Research Institute – Developer

Clarence Robison – Univ. Idaho – GIS technician

Ian Ratcliffe – University of Nebraska – Remote Sensing Specialist

Ricardo Trezza – University of Idaho – Professor

David Thau, Google, Inc. – Earth Engine Advocate

Tyler Erickson, Google, Inc. – Earth Engine Advocate

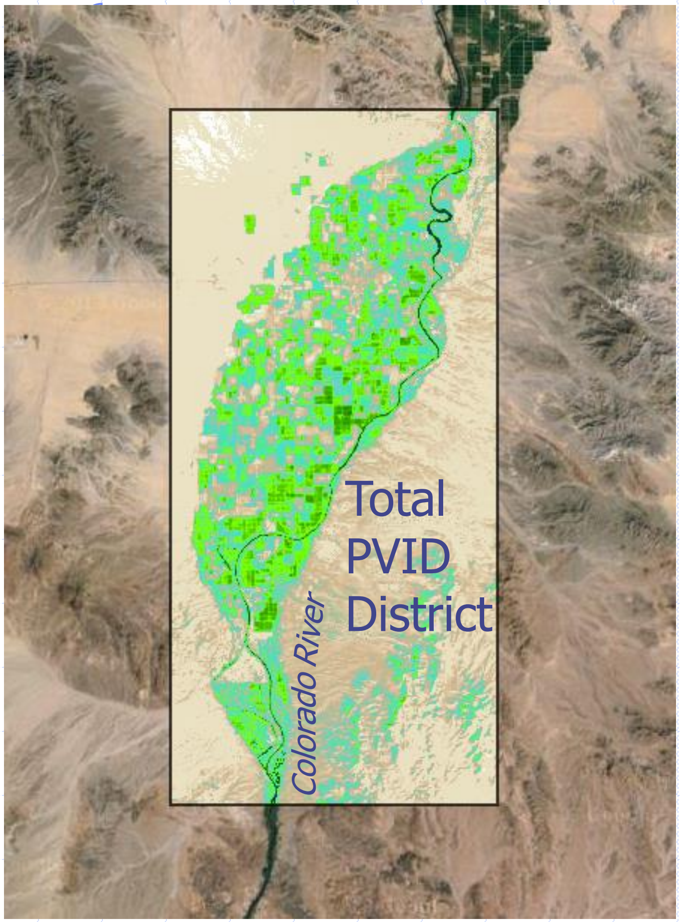
Noel Gorelick, Google, Inc. – Earth Engine Advocate

Rebecca Moore, Google, Inc. – Manager, Earth Engine / *Visionary*

Why an Evapotranspiration Tool on Google Earth Engine?

- Earth Engine (EE) has enormous computing and storage power
- EE has essentially free access
- EE has strong developer support
- ET information is needed across the Global spectrum
- Google supports and encourages developers to 'change the world' regarding access to spatial information on the environment, natural resources, conservation and climate change

Google Earth Engine App --- EEFlux



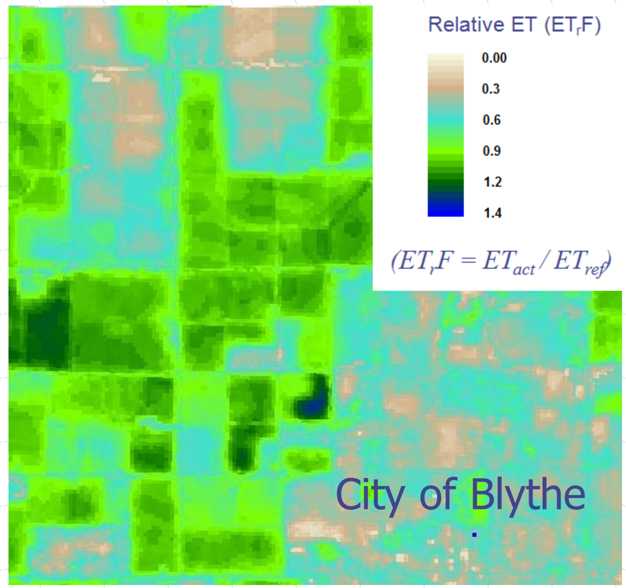
Earth Engine Evapotranspiration Flux

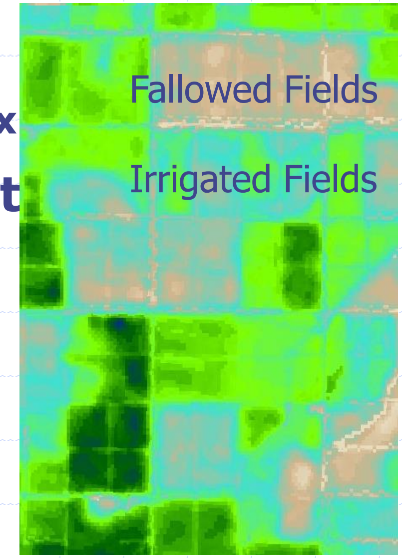
Palo Verde Irrigation District

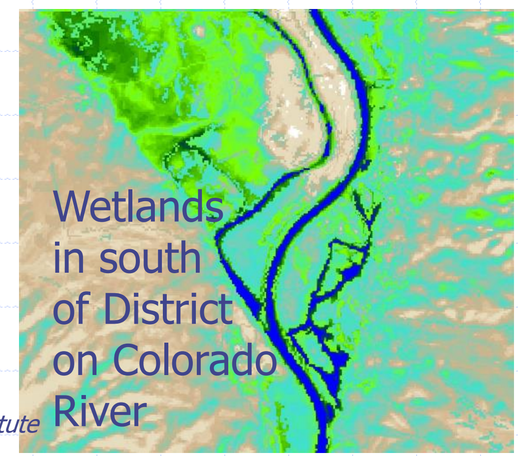
Blythe, California – Jan. – Dec. 2008

-- Landsat 5 imagery

Dec.







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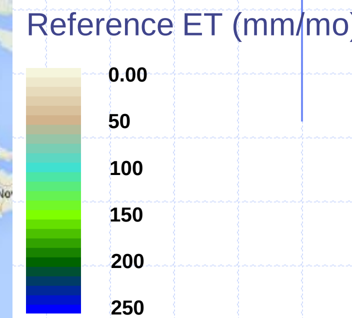
Computations are based on a complete surface energy balance ***(METRIC)***

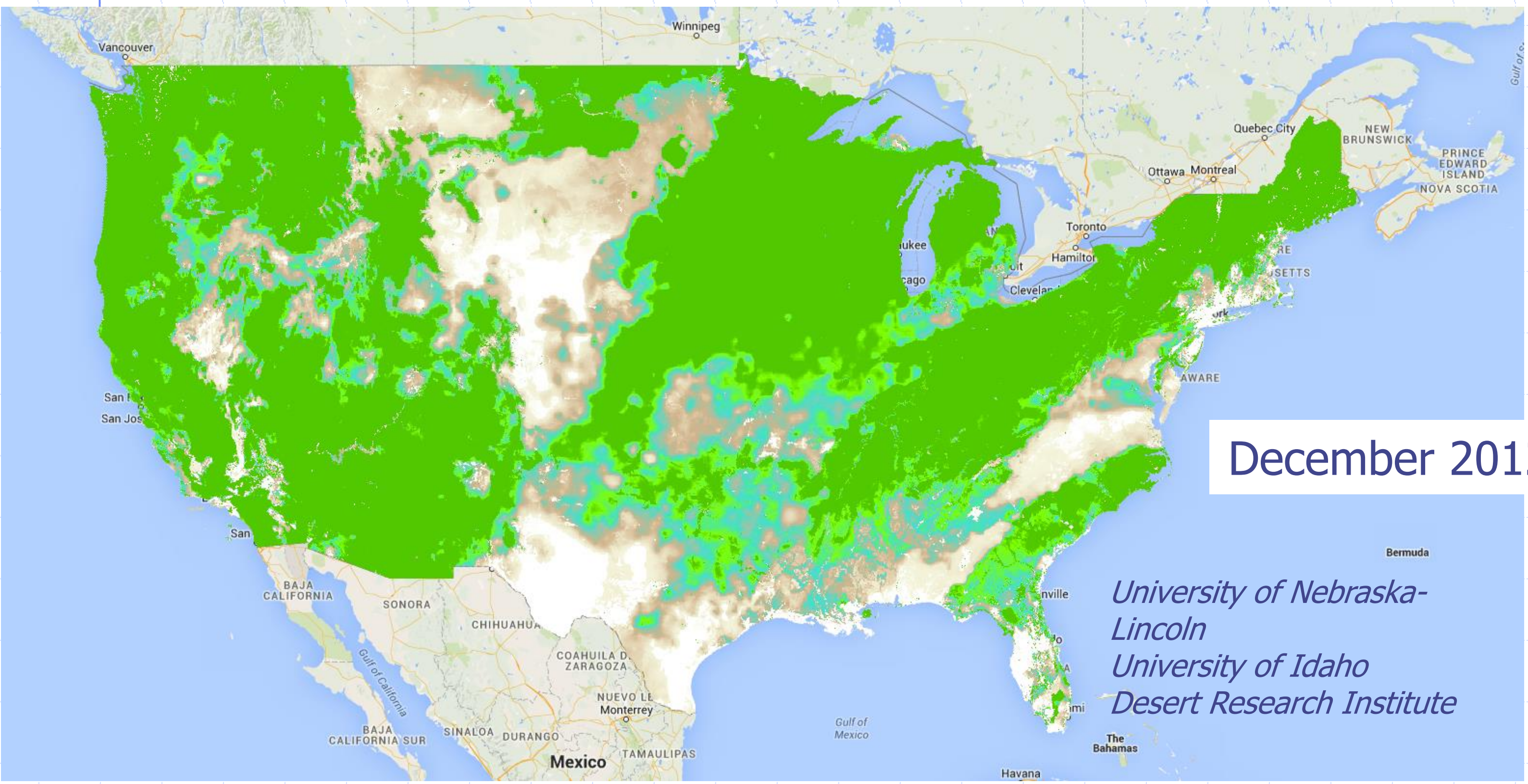
Reference ET on the Google Earth Engine EEFlux App.



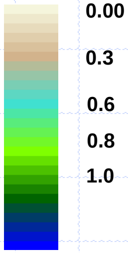
Reference ET calculated using the ASCE Standardized Penman-Monteith Equation for the Tall Reference (Alfalfa) --computed from the GridMET data set of Abatzoglou (2012)

The Soil Surface Evaporation Component of the Google Earth Engine EEFlux App.

--- **Evaporation from Bare Soil** --- used to calibrate the EEFlux Evapotranspiration Surface Energy Balance to account for Precipitation Effects on ET



Evap. Coef. (K_e)



$(K_e = E_{act} / ET_{ref})$

--computed from the GridMET weather data set of Abatzoglou (2012)

-- GridMET is traceable to NLDAS and PRISM data sets

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Next Steps

Automation of:

- Cloud detection and mitigation
- Calibration of EEFlux energy balance for highest accuracy
- Time integration to produce monthly and annual ET volumes
- Mosaicing paths

Development of a User Console

- to save project information
- free access to EEFlux API's (level 1)
- level 2 means to permit some degree of tuning

National and Global application

American Society of Civil Engineers – Proposed Tier System for Characterizing Methods for Remote Sensing of ET

Task Committee on Remote Sensing of Evapotranspiration

-- Ayse Kilic, Univ. Nebraska-Lincoln, Chair

Purpose:

Help perspective users of methods and data understand:

- internal mechanics
- assumptions and limitions
- expected accuracies

Committee period: May 2015 – April 2018

Tier 1. (lowest tier) - Cursory exploration of spatial distribution of water consumption according to the distribution of vegetation

-- Use general ET vs. vegetation indices or general Kc vs. vegetation indices

-- Useful for:

Identifying irrigated vs. nonirrigated areas,
showing greeness and wetness of riparian systems, etc.
for atlas-level types of work.

Tier 2. – Short-wave and/or thermal-based ET products where limited human overview is exercised, and where the procedure has a limited physical basis.

--Methods may include
scaling from vegetation indices and
scaling of reference ET by surface temperature.

--Applications may include:
a. annual reporting where low to moderate accuracy is acceptable due to a trade-off of accuracy with rapid or unsupervised computation
b. national or global surveys on water consumption or production of atlases

Tier 3. – ET production systems based on a full surface energy balance including:

albedo
surface temperature
soil heat flux
surface roughness
surface wetness
boundary layer instability

Tier 3 systems should be useful for parameterizing or driving:

a. hydrologic models including ground-water recharge and depletion estimation in noncomplex terrain
b. surface water accounting on streams and streamflow depletion
c. general basin-wide water balances in relatively noncomplex terrain, and
d. developing crop coefficients.

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Tier 4. (top tier) – ET production systems to be used for supporting:

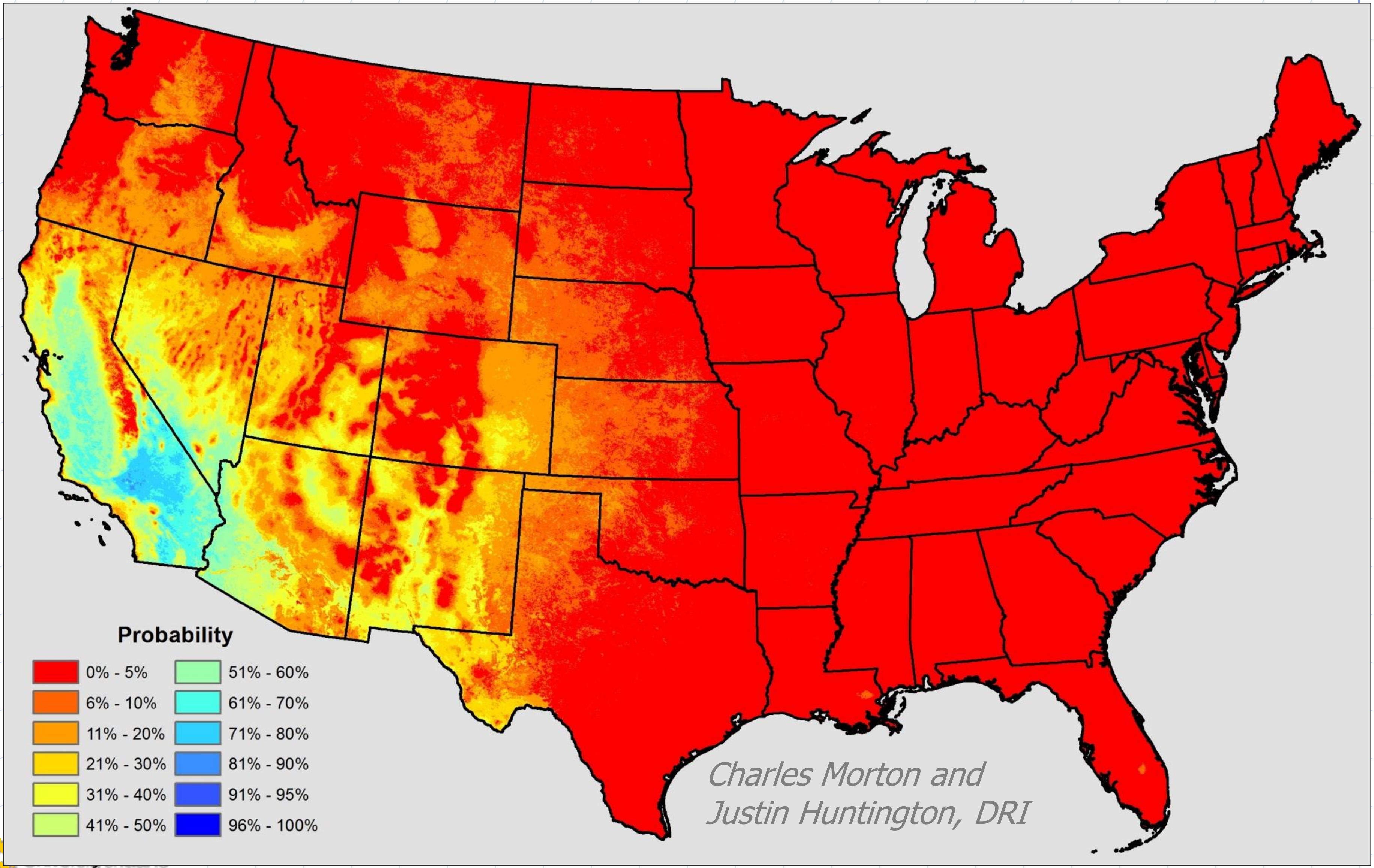
a. management of water rights
b. water transfers
c. litigation
d. streamflow depletion for mitigation and multi-state agreements.

Tier 4 systems employ a full surface energy balance and include:
--algorithms for calculating solar radiation on complex slopes and variation in aerodynamics over complex terrain
--use time integration schemes and cloud mitigation schemes that produce moderate to high accuracy at the monthly scale.
--employ one, two or three source surface models, depending on the aerodynamic scheme

Tier 4 systems employ a sufficient amount of human oversight and intervention and professional, expert review.

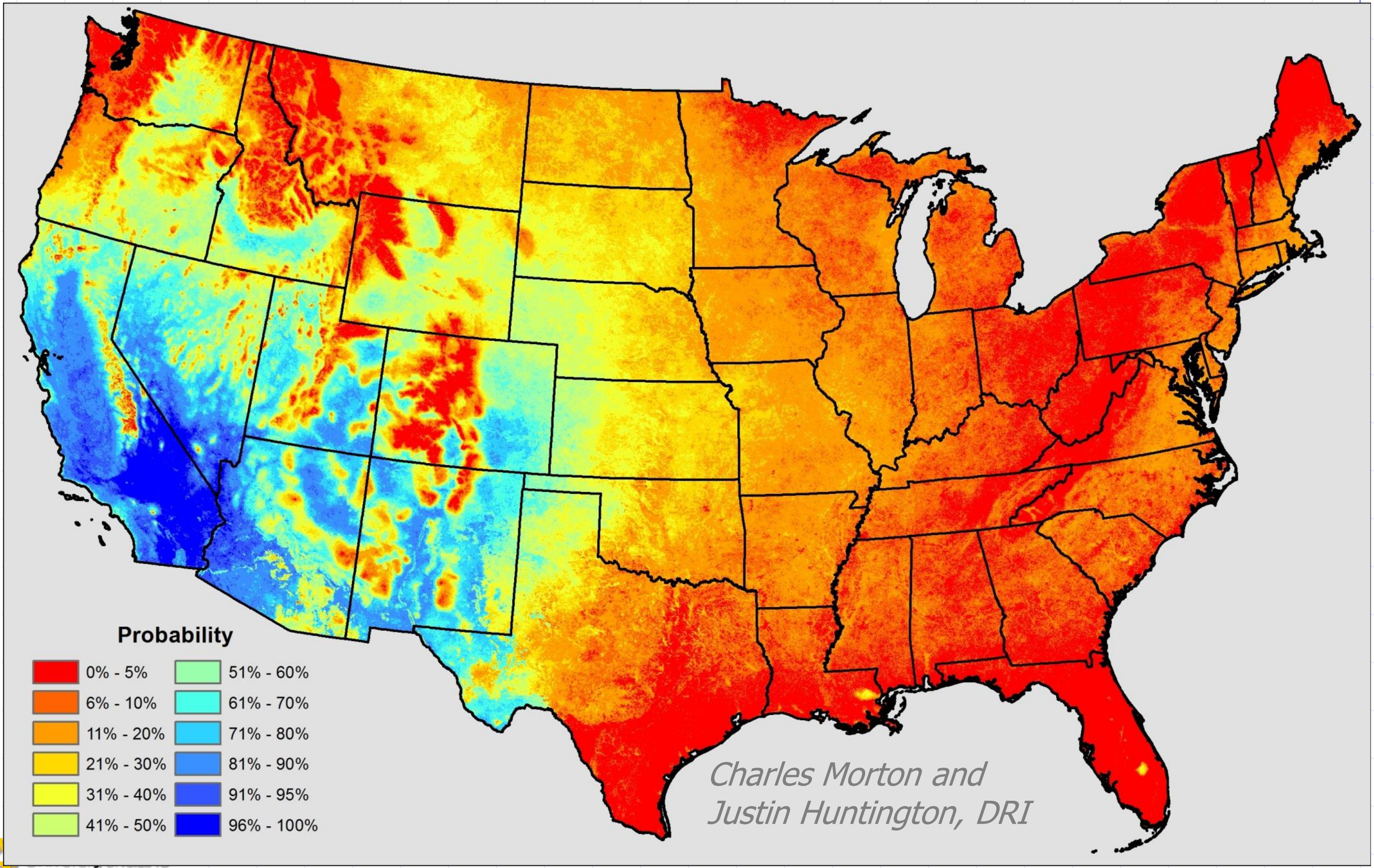
1 Satellite (image each 16 days)

Probability of producing a good estimate of Water Consumption over any given year (having a Cloud-free Image at least every 32 days during the growing season)



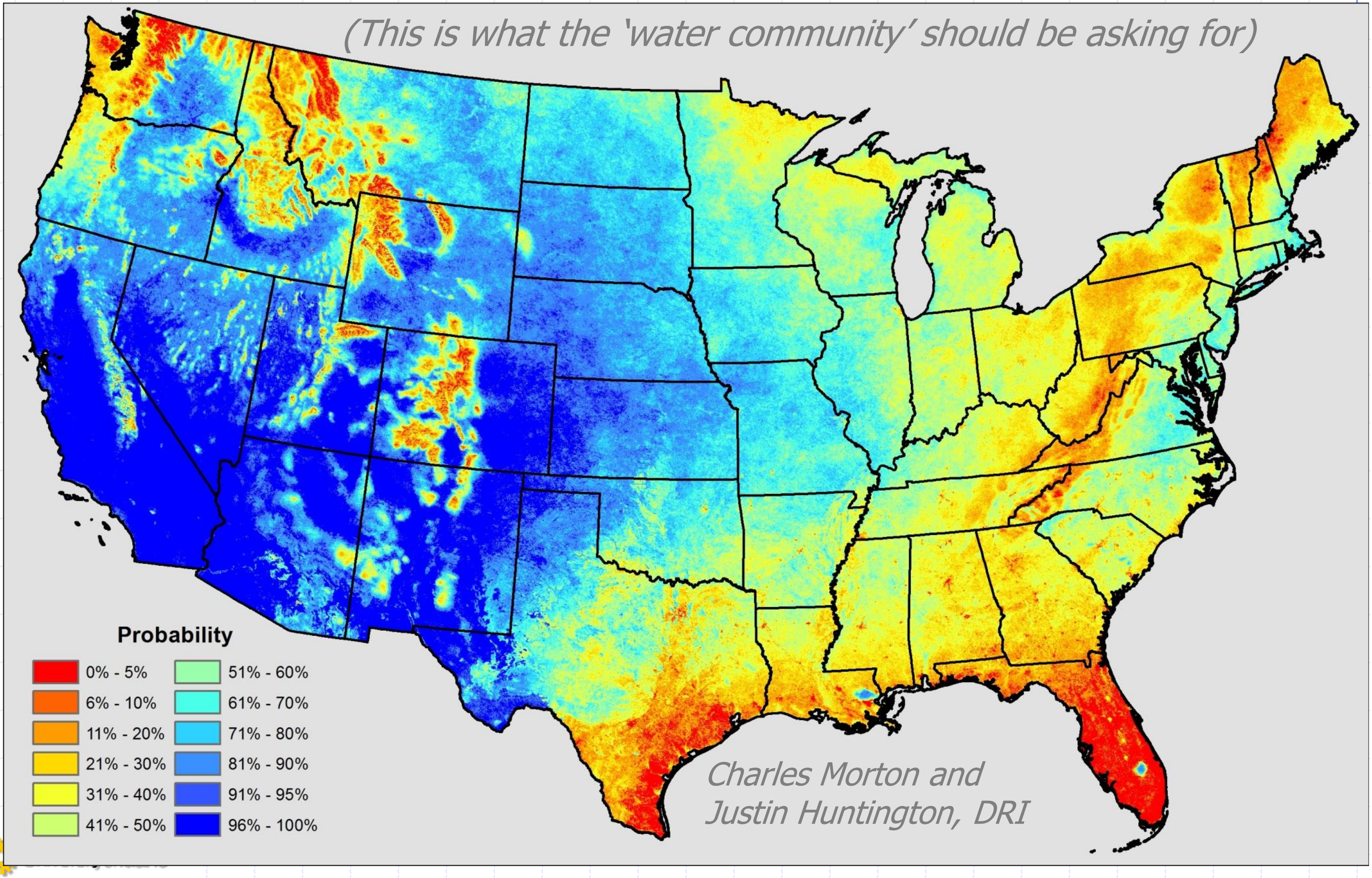
2 Satellites (image each 8 days)

Probability of producing a good estimate of Water Consumption over any given year (having a Cloud-free Image at least every 32 days during the growing season)



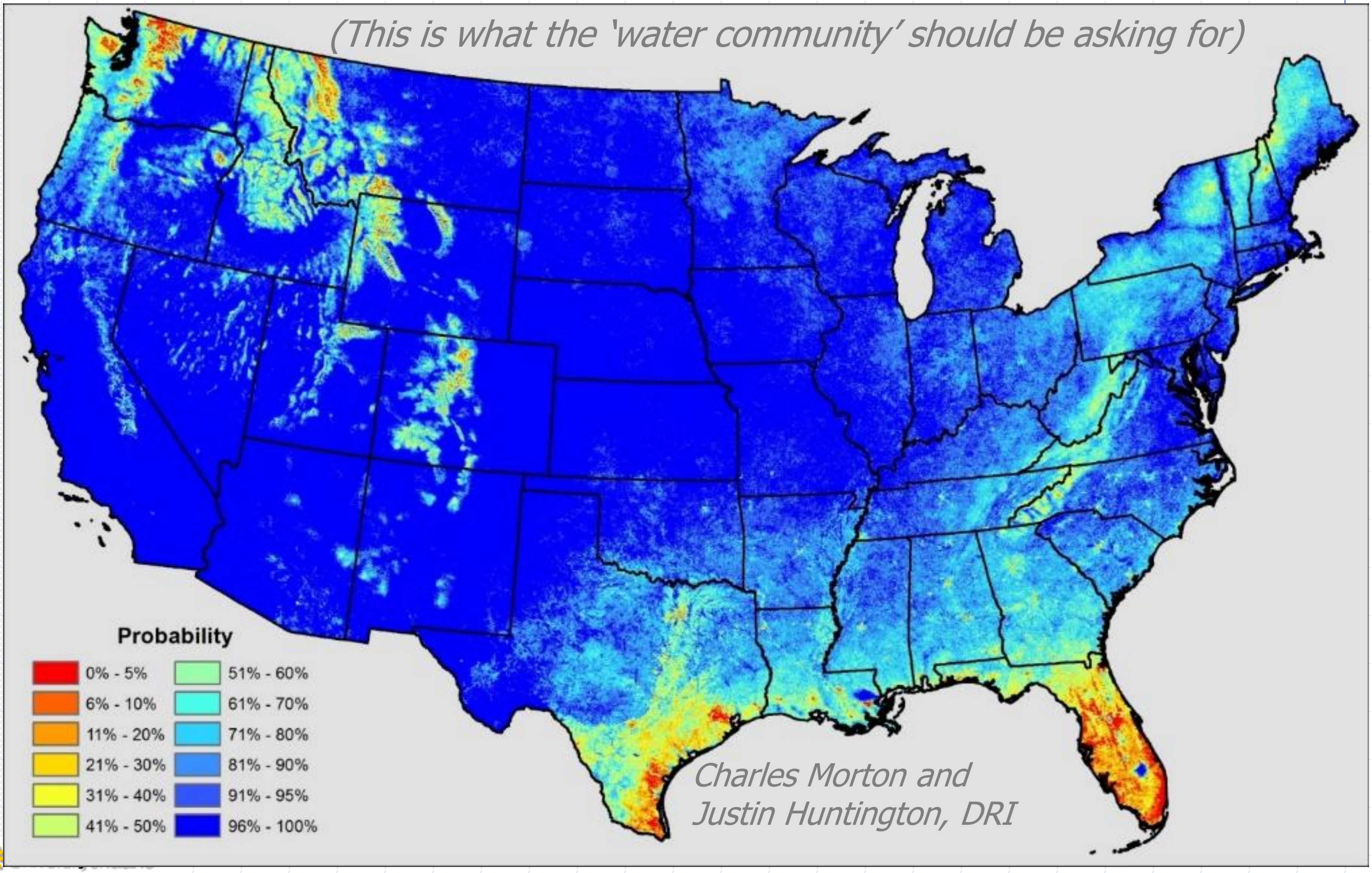
4 Satellites (image each 4 days)

Probability of producing a good estimate of Water Consumption over any given year (having a Cloud-free Image at least every 32 days during the growing season)



8 Satellites (image each 2 days)

Probability of producing a good estimate of Water Consumption over any given year (having a Cloud-free Image at least every 32 days during the growing season)



A Landsat-based "Earth-Selfie" concept

- Cost: Less than 3 coffee-latte's per American per year
- Support SIXTEEN Landsats in orbit
- *DAILY* Earth-Selfie's
- Consider:
  - *99% of all Americans blow at least $10 per week on superfluous things: cafe-lattes; bottled water; movies; gasoline to motor three blocks to the market-place or across town to look for designer jeans.*
  - *However, we don't want to spend the <$0.50 PER YEAR per American needed to launch and operate a Landsat that takes field-scale 'selfies' of our Nation.*
  - *Less than $6 per American PER YEAR would place SIXTEEN Landsats into orbit, giving us DAILY Selfies of the entire Nation.*

  Can you believe what that would be like? A Landsat 'Selfie' EVERY DAY???

$800 million/LS
÷8 years
x 16 LS
÷ 300 million Americans
= $5.30 per American per year

Not having daily Landsat coverage seems to be very economically damaging to the United States

University of Idaho

Thank you.